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Complementarity in R&D cooperation strategies*

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Abstract

This paper assesses the performance effects of simultaneous engagement in R&D cooperation with different partners (competitors, clients, suppliers, and universities and research institutes). We test whether these different types of R&D cooperation are complements in improving productivity. The results suggest that the joint adoption of cooperation strategies could be either beneficial or detrimental to firm performance, depending on firm size and specific strategy combinations. Customer cooperation helps to increase market acceptance and diffusion of product innovations and enhances the impact of competitor and university cooperation. On the other hand, smaller firms also face diseconomies in pursuing multiple R&D cooperation strategies, which may stem from higher costs and complexity of simultaneously managing multiple partnerships with different innovation objectives.

1. Introduction

Both the industrial organization and the management literature on strategic alliances have devoted substantial attention to the analysis of R&D cooperation. The industrial organization literature has largely focused on the effects of R&D cooperation between competing firms on R&D investment and welfare (e.g., Amir et al., 2003; Martin, 1995; Suzumura, 1992).[1] In practice, however, R&D links formed by firms with suppliers, customers, or research institutes and universities are as frequent as cooperation with competitors, and a substantial share of innovating firms are engaged in R&D cooperation with several partners simultaneously (Belderbos et al. 2004a, 2004b; Leiponen, 2001; Tether, 2002; Veugelers and Cassiman, 2003).

The alliance literature has emphasized the complexity of rationales behind cooperative strategies and the need to establish multiple alliances (e.g., Contractor and Lorange, 2002; Das and Teng, 2002; Tyler and Steensma, 1995). Alliance networks, their determinants, and composition have mostly been studied from the perspective of social network theory (e.g., Gulati, 1995).

The fact that many firms are engaged in multiple cooperative agreements raises the question whether there are synergetic effects between these strategies -- i.e., whether forming a new alliance in R&D enhances the effectiveness of other existing R&D collaborations. Such a synergy, or complementarity, has been formally defined by Milgrom and Roberts (1990) and is assumed to exist if the implementation of one practice or strategy increases the marginal return to other practices. A number of studies have examined complementary effects of practices related to workplace organization, use of information technology, and obstacles to innovation (Bresnahan et al., 2002; Ichniowski et al., 1997; Mohnen and Röller, 2005).

Despite the growing literature on R&D cooperation in both the fields of management and industrial economics, surprisingly little evidence has emerged on the interaction of different cooperation strategies in innovation. Aurora and Gambardella (1990) find a positive correlation between residuals of equations explaining large pharmaceutical firms' R&D agreements with research institutes, minority participations, and acquisitions of new biotechnology firms. They take this to indicate that networked R&D strategies are most effective for firms active in biotechnology. However, Aurora (1996) points out that the testing methodology of correlating residuals cannot serve as conclusive evidence of the greater effectiveness of joint adoption of the different

[1] Exceptions are models that examine vertical cooperation (Steurs, 1995) and vertical alongside competitor cooperation (Atallah, 2002).

cooperation strategies.[2] Other empirical work has examined the impact of R&D cooperation on firms' innovation output: sales of innovative products (e.g., Criscuolo and Haskell, 2003, Faems et al., 2004; Janz et al., 2003; Klomp and van Leeuwen, 2001; van Leeuwen, 2002; Lööf and Heshmati, 2002) but in most cases aggregated over cooperation types. Belderbos et al. (2004b) explicitly examine the differential impacts of R&D cooperation with customers, suppliers, competitors, and research institutes and universities on labor productivity and sales of innovative products for a large sample of Dutch firms, but do not analyze potential complementarities between these R&D cooperation strategies.

This paper is the first to examine whether different types of R&D partnerships are complementary. We distinguish four types of partner-specific innovation strategies: cooperation with competitors, customers, suppliers, and universities and research institutes. Building on our previous work (Belderbos et al., 2004b), we analyze the possible complementarities in these cooperation strategies in their effects on labor productivity for a large sample of innovating firms in two waves of the biannual Dutch Community Innovation Survey (1996, 1998) and production statistics. We apply an appropriate testing framework for complementarity between multiple practices when these practices are measured as discrete variables. Based on a review of related theoretical and empirical literature we find that pursuing different types of R&D cooperation, to the extent that they also relate to pursuit of different innovation objectives and increase managerial costs and complexity, may not necessarily result in improved performance. Our empirical results suggest mixed effects of joint cooperation strategies, with substantial differences between large and small firms.

The remainder of the paper is organized as follows: Section two provides a review of the theoretical and empirical literature on R&D cooperation and firm performance. In section three we describe the model and the econometric methodology used to examine complementarity between cooperation strategies. The empirical model, data, and empirical findings are presented in section four. The final section contains our conclusions, a discussion of caveats, and suggestions for further research.

[2] Estimated correlations between residual terms may be the result of common omitted exogenous variables or measurement errors. Even in the case of robust correlation between practices, there is no guarantee that decision makers were sufficiently well informed such that they indeed chose efficiency or output enhancing combinations of practices.

2. Literature review

Previous research has argued that different types of R&D cooperation may serve different purposes (Belderbos et al., 2004a; Teece, 1980). Firms seek cooperation with customers to source new ideas for innovations and to reduce the risk of uncertainty that is associated with market introduction of these innovations (von Hippel, 1988). Collaboration may also be essential to insure market expansion when products are novel and complex or when they require adaptations in use by the customers (Tether, 2002).

In contrast, cooperation with suppliers is often related to input quality improvement and cost reductions through process innovation (Hagedoorn, 1993). Cooperation with rivals is often motivated by the need to share R&D costs (Miotti and Sachwald, 2003), the pursuit of synergistic effects through pooling of the firms' resources (Das and Teng, 2000), or dealing with regulations and industry standards (Nakamura, 2003). Cooperation with universities and research institutes is generally more aimed at radical breakthrough product innovations that may open up entire new markets or market segments (Monjon and Waelbroeck, 2003; Tether, 2002). Universities are also more likely to be a firm's partner in new technological fields or when the speed of technological change is high and commercial outcome of cooperation is uncertain (Belderbos et al., 2004a; Hall et al., 2003; Rahm et al., 2000).

Few theoretical studies have examined the interaction between different innovation or cooperation strategies.[3] Athey and Schmutzler (1995) consider the simultaneous implementation of two innovation strategies by a single firm. They find complementarity between product and process innovation strategies. Investments that improve product design increase output, which in turn increases the returns to process innovations. They also concede that this complementarity between investments in product and process innovations may not always be achievable due to the increased demands on information processing capabilities and attention of workers and managers that they require.[4] Lin and Saggi (2002) model R&D cooperation between competitors, where firms can choose between cooperation in product R&D, process R&D, or both. They find that cooperation in product R&D leads to increases in both types of R&D, but that full cooperation (in both process and product R&D) leads to a reduction in R&D investments. This result arises because cooperation in process R&D reduces the

[3] Theoretical models that link R&D cooperation and performance have focused primarily on R&D cooperation with a single competitor (e.g., Cabral, 2000; Kline, 2000; Martin, 1994; Suzumura, 1992).
[4] A case study by Henderson and Clark (1990) suggests the importance of such managerial complexities.

incentives of the firms to invest in R&D in order to compete on costs and price in the output market. In a related paper, Rosenkrantz (2003) models the simultaneous decisions to engage in R&D cooperation and the levels of product and process R&D investments. Here cooperation with rival firms leads to a shift in R&D efforts towards product R&D. Cooperation leads to a reduction in price competition accompanied by reduced output, which reduces the incentives to engage in process R&D. Atallah (2002) presents a model of spillovers and R&D cooperation decisions by two vertically related duopolies and generally finds a more positive effect of combined (both with suppliers and competitors) cooperation strategies. Although results depend on the degree of vertical and horizontal spillovers that cooperation can internalize, a finding is that the cost-reducing impact of vertical cooperation leads to increased R&D expenditures under horizontal cooperation.

Leyden and Link (1999) focus on R&D cooperation with public research institutions. They examine the case of multiple partners in a research joint venture (RJV) involving a public research laboratory. They argue that an increase in the number of cooperating firms in such a RJV leads to a significant increase in monitoring costs and a reduced ability of member firms individually to appropriate the research output. These costs and appropriability issues can outweigh the benefits of the RJV related to economies of technological scope. A complicating issue in simultaneously managing R&D partnerships with multiple partners is the associated increase in complexity and coordination costs. Bolton and Dewatripont (1994) point out that a tradeoff exists between firms' specialization and coordination. When coordination and communication efforts are dispersed on multiple cooperation arrangements, this increases the organizational costs of processing and communicating information. Specialization and focus on collaboration with a smaller set of partners reduces the costs of communication, and this may offset the benefits of multiple partner cooperation.

The empirical literature on performance effects of R&D cooperation has tended to explore the direct performance effects of process and product innovation on firm performance (e.g., Geroski, 1991; Huergo and Jaumandreu, 2004; Vivero, 2004). The majority of empirical models that included R&D cooperation have used an aggregated cooperation variable and often found a positive impact of engaging in R&D cooperation on innovation performance: sales of innovative products (e.g., Criscuolo and Haskell, 2003; Janz et al., 2003; Klomp and van Leeuwen, 2001; van Leeuwen, 2002; Lööf and Heshmati, 2002), patenting (Brouwer and

Kleinknecht, 1999; Vanhaverbeke et al., 2002), sales growth (Cincera et al., 2003), and firms' stock prices (Wu and Wei, 1998).

A number of empirical papers have also examined the effect of different cooperation types, but with ambiguous results. Monjon and Waelbroeck (2003) investigate the effects of collaboration and spillovers on innovation success, distinguishing between innovations new to the firm (incremental innovations) and innovations new to the market. They find that cooperation with universities increases the probability of the introduction of innovations that are new to the market.[5] However, cooperation with competitors and (foreign) suppliers reduces the probability of introduction of such innovations. Cincera et al. (2003) distinguish between overseas and domestic R&D collaboration by Belgian firms and find a positive impact on productivity of the latter but a counter-intuitive negative impact of the former. Lööf and Heshmati (2002) include a selected group of cooperation types in an innovation output equation for Swedish firms and find that cooperation with competitors and universities affects output levels positively, while cooperation with customers hampers innovation. Belderbos et al. (2004b) find that supplier and competitor cooperation has a significant impact on labor productivity growth, while cooperation with customers and universities and research institutes positively affects growth in sales of innovative (new to the market) products.

The empirical literature on R&D alliances has only recently begun to assess the performance effects of R&D cooperation (Das and Teng, 2002). One line of research has examined why not all R&D partnerships are equally profitable. Partnerships in which firms have high compatibility in organizational processes and partner-specific absorptive capacity allowing for effective transfer of know-how tend to outperform partnerships in which overlapping knowledge is narrow (Dyer and Singh 1998; Mora-Valentin et al., 2004).[6] Other emerging evidence points out that a network of R&D alliances should be organized such as to minimize redundancies in knowledge sharing (e.g., Vanhaverbeke et al., 2002) and that large alliance networks are not necessarily generating the highest innovative output, especially in the presence of product market competition between consortium members (Bransteter and Sakakibara, 2002).

[5] Siegel (2003) finds higher innovative performance for firms located in university science parks, which is likely to be due to a more intensive interaction and collaboration between firms and universities.
[6] Anbarci et al. (2002) also stress the importance of complementarity between cooperating firms' R&D processes and R&D inputs in RJVs.

Overall, previous empirical work appears to suggest a positive impact of R&D cooperation on firm performance. The complementarity between different R&D cooperation strategies, on the other hand, may be limited due to increased complexity and cost of managing multiple R&D partnerships with different objectives, limited time and attention of management and R&D personnel, and possible loss of appropriability when collaborating with public institutions. The first two concerns are likely to be greater for small firms than for larger firms. In the sections below we explore whether combining individual and multiple R&D cooperation partnerships increases labor productivity and if these results differ between large and small firms.

3. Complementarity in R&D cooperation strategies

We aim to identify empirically the complementarities that exist between four types of R&D cooperation strategies: cooperation with competitors, customers, suppliers, and universities. Our methodology follows a 'production function' approach, by which we directly estimate the contributions of combinations of strategies to the relevant output measure. This approach has been shown to be more appropriate than the 'adoption' approach that relies on correlation of residuals from the reduced-form equations (Arora, 1996, Athey and Stern, 1998). To formalize the hypotheses, we specify a general production function for the firm: the firm maximizes a performance measure $f(x)$, with respect to the vector of four R&D cooperation strategies $\boldsymbol{x}$ = (competitor, customer, supplier, university).

When the practices are measured by continuous variables, complementarity implies that cross-partial derivatives of the function f with respect to practices are positive (e.g., Baumol et al., 1988). When the practices have discrete values, the derivatives are replaced by unit differences, and conditions for complementarity can be expressed as comparisons between combinations of practices. The conditions for complementarity between two practices (e.g., x_1 and x_2) correspond to the following four inequalities, where at least one of the inequalities has to hold strictly: [7]

[7] This definition is also called 'strict supermodularity' (Milgrom and Roberts, 1990) and is equal to complementarity in the conventional sense of scope economies (adoption of practice B strictly increases the marginal returns of adoption of practice A). If supermodularity is not defined 'strictly', it does not exclude the possibility that practice B has no impact on the returns to practice A.

$$f(1,1,0,0) + f(0,0,0,0) - f(1,0,0,0) - f(0,1,0,0) \geq 0 \quad \text{(1-a)}$$

$$f(1,1,1,0) + f(0,0,1,0) - f(1,0,1,0) - f(0,1,1,0) \geq 0 \quad \text{(1-b)}$$

$$f(1,1,0,1) + f(0,0,0,1) - f(1,0,0,1) - f(0,1,0,1) \geq 0 \quad \text{(1-c)}$$

$$f(1,1,1,1) + f(0,0,1,1) - f(1,0,1,1) - f(0,1,1,1) \geq 0\,. \quad \text{(1-d)}$$

These conditions imply that higher returns are achieved when the two practices are used together compared to a situation when they are used separately, for at least one combination of the other practices. The definition for substitutability (subadditivity)[8] is identical to the definition above except that 'larger' is replaced by 'smaller'. We can conveniently use an indicator function $I_{D=(r,s,t,u)}$ to rewrite the function f as:

$$f(x_1, x_2, x_3, x_4) = \sum_{r=0}^{1}\sum_{s=0}^{1}\sum_{t=0}^{1}\sum_{u=0}^{1} \beta_{rstu} I_{(x_1,x_2,x_3,x_4)=(r,s,t,u)} \quad (2)$$

where we normalize $f(0,0,0,0)$ to zero. In the empirical model this implies that we estimate a constant term as well as 15 dummy variables for exclusive (combinations of) cooperation strategies. Previous research examining complementarity between more than two practices has often resorted to estimating pair-wise interaction effects.[9] This approach is problematic because it omits relevant terms and is prone to an omitted variable bias, which is likely to lead to incorrect inferences (Lokshin et al., 2004). We apply a proper complementarity or substitutability test, which requires consideration of the complete set of organizational practices and hence involves the full set of multiple linear inequality restrictions.[10] While the testing methodology allows us to examine overall complementarity of substitutability between any two practices, the coefficients β indicate the performance impact of adopting (combinations of) cooperation strategies compared to a strategy of no R&D cooperation.

[8] It may be argued that the term 'subadditive' used in Milgrom and Roberts (1990) better captures the meaning of the relationship between the strategies. Substitution in our context does not imply that one strategy can be substituted for another, but rather that their joint use results in suboptimal performance.
[9] Recent examples include Black and Lynch (2001), Bresnahan et al. (2002), and Caroli and Van Reenen (2001). Exceptions are Mohnen and Röller (2005) and Leiponen (2005).
[10] The testing procedure is based on a minimum distance or LR test and is outlined in the appendix A: for a more detailed treatment we refer to Lokshin et al. (2004).

4. Empirical model, data, and descriptive statistics

We examine the impact of R&D cooperation on the growth in labor productivity from 1996 (t-1) to 1998 (t). We estimate the following growth in productivity equation:

$$\Delta \log(prodv)_i = \alpha + \sum_{r=0}^{1}\sum_{s=0}^{1}\sum_{t=0}^{1}\sum_{u=0}^{1}\beta_{rstu} I_{(co,su,cu,un)=(r,s,t,u)} + \delta W_i + \theta \log(prodv)_i + \varepsilon_i \qquad (3)$$

where co=competitor cooperation, su= supplier cooperation, cu=customer cooperation, and un=cooperation with universities and research institutes. All right hand side variables are measured at time t-1, while $\Delta \log(prodv)_i = \log(prodv_{it}) - \log(prodv_{i,t-1})$ is the growth in productivity from period t-1 to t measured as value added per employee. The indicator function *I* captures all exclusive combinations of cooperation strategies where the case of 'no cooperation' is normalized to zero corresponding to equation (2).

Lagged *log(Prodv)* is the level term of the dependent variable taken in the base year (1996). Firms that are highly productive and are at the frontier of productivity may be less likely to have strong growth rates in productivity than firms that are followers. In that case we expect θ to fall within the interval [-1,0]. If θ is zero, this effect is absent, and there is no gradual convergence between leading firms and productivity laggards. If θ is –1, a productivity lead in one period is fully neutralized in the next, and past productivity has no impact on future productivity levels.[11]

Following previous empirical studies we include a number of other variables that are expected to affect labor productivity growth. These are captured by the vector W. Since many studies have documented a positive

[11] To see this one can simply rewrite the relevant part of (1) as $\log(prodv_t) = ...(1+\theta)(prodv_{t-1})$. In the absence of the possibility of including fixed firm effects, inclusion of the lagged level term has the advantage that it partly adjusts for unobserved firm attributes that are relatively constant over time. A related advantage is that it allows for the effects of the exogenous variables to be interpreted as one-period Granger-causation. The Granger approach to the question of whether *x* causes *y* is to see to what extent the current *y* is explained by past values of *y* and then to consider whether adding lagged values of *x* can improve the statistical explanation. The variable *y* is said to be Granger-caused by *x* if the coefficients on the lagged values of *x* are statistically significant

impact of own R&D on productivity at the firm level (e.g., Grilliches and Mairesse, 1984), our model controls for the R&D intensity of the firms.

There is a large body of empirical literature examining the sources of productivity growth and in particular the role of inter-firm knowledge spillovers (e.g., Adams and Jaffe, 1996; Cincera and Van Pottelsberghe, 2001). These studies have generally confirmed that knowledge spillovers have a positive impact on productivity growth. The variable 'spillovers' is included to control for such external knowledge spillovers. The firms are asked in the CIS survey to rate on a Likert scale the importance of various external sources of information for the firm's innovation activities. We include the sum of scores of importance of information from competitors, suppliers, customers, and universities.[12]

We want the coefficients for R&D cooperation to measure the full impact of R&D collaboration on productivity growth. In order to separate the effect of the incoming spillovers from the effect of cooperation (cooperation can have a direct effect on productivity but will at the same time increase the reported incoming spillovers from the collaboration partner), we adjust the spillover variables from the influence of formal cooperation. This is achieved by taking the residuals obtained from regressing the full spillover variable on the cooperation variable and a set of industry dummies. In this way, we estimate the full impact of formal cooperation, by separating spillovers due to purposeful informational exchanges that arise in formal cooperative arrangements from spillovers that are not due to such cooperation (e.g., arising from market contacts with suppliers and customers).

The *W*-vector further includes fixed capital investment, firm size, dummies controlling for foreign and domestic groups, and dummies for the industry of the firm at the two-digit level. To control for the potential impact of mergers or acquisitions on the growth of productivity we include a dummy variable 'merger', taking the value 1 if new establishments were acquired during 1994-1996.

Data and Descriptive statistics

[12] Several alternative indirect measures of spillovers have been used in previous empirical work -- e.g., based on uncentered correlation (Jaffe, 1986), Euclidean distance, and geographical distance. According to comparative study of various spillover measures by Kaiser (2002b) both uncentered correlation and direct measures (used in our model) appear to capture spillovers quiet accurately.

The empirical analysis uses data from two consecutive Community Innovation Surveys (CIS) conducted in 1996 and 1998 in the Netherlands, as well as information from the census of manufacturers in the same years. Variables used in the statistical analysis are listed and described in Table 1, and descriptive statistics are displayed in Table 2. In total there were 2353 innovating firms with data available in both the 1996 and 1998 surveys. These firms were linked to the production statistics data. The data are at the establishment level and include manufacturing as well as service firms. Due to the missing values for some of the explanatory variables, the complete sample includes 1992 firms.[13]

The distribution of cases by industry and descriptive statistics are presented in Tables 2 and 3. There are 589 firms (30%) with R&D cooperation of any type among the innovating firms in the combined sample. Competitor cooperation, the focus of much of the industrial organization literature on R&D cooperation, is certainly not the most frequently adopted cooperation strategy (204 cases). Supplier cooperation is most frequently adopted, with 343 firms indicating to be engaged in this type of strategy, followed by customer cooperation (329 firms), and university cooperation (249). Some 1403 firms reported to have none of the four types of links. The comparison across industries indicates that the propensity to cooperate is not dissimilar between services and manufacturing industries. Cooperation is comparatively more frequent in (petro)chemicals, metals, and business services. Science-based industries such as electronics and chemicals, but also the food and metal industries, report a relatively high share of university cooperation.

Table 4 shows the occurrence of particular combinations of cooperation strategies: the number of cases where the dummies representing exclusive combinations of cooperation strategies take the value 1. Vertical cooperation is most prominent: supplier only (94), customer only (76), combined (74), or both combined with university cooperation (40). Some 50 firms have cooperative agreements of all four types. A number of cooperation strategies are not often combined and have relatively few observations: competitors and suppliers with or without university cooperation (15, 13), and competitor and customer with or without university cooperation (16, 18). In the analysis, we make a distinction between 'small' firms, defined as firms with less than 100 employees, and 'large' firms. The sub-samples have 836 (large) and 1156 (small) firm observations. As

[13] A more detailed description of the data is given in Belderbos et al. (2004a).

one would expect, cooperation is most prevalent among large firms. In the sub-samples the number of cases of particular exclusive combinations of cooperation strategies is further reduced to single digit numbers.[14]

5. Empirical results

Table 5 reports the results of equation (3) in the first column. Of the single cooperation strategies, competitor cooperation and supplier cooperation are significantly positive. In two cases, combinations of two strategies have a positive and significant impact, one triple strategy is positive and significant as well, and so is the strategy of combining all four types of R&D cooperation. None of the cooperation dummy variables have significantly negative impacts. Overall, these results clearly confirm a positive impact of R&D cooperation on productivity growth. A general observation is that the highest coefficients (competitor-customer, competitor-supplier) are observed for two joint strategies, whereas adding a third or fourth strategy does not increase productivity growth. The lagged productivity variable is highly significant and negative, indicating that productivity leaders are less able to show further productivity growth. The estimated coefficient indicates that a one percent higher past productivity is associated with half of a percent less productivity increase. Incoming knowledge spillovers, investment intensity, and R&D intensity have the expected positive and significant effects. Productivity growth is also higher for foreign-owned affiliates, while the merger-variable is insignificant.

The estimation results for equation (3) for the separate samples of small and large firms are presented in columns 2 and 3 of Table 3. The Chow test rejects the null of no difference between small and large firms. In general, fewer significant effects are observed, which may be related to the smaller sample sizes and the fact that the exclusive state dummies include fewer observations. Not one significant effect of adopting a single cooperation strategy is observed for large firms, while for small firms supplier cooperation has a relatively large and significant positive impact. Small firms furthermore benefit from combining customer cooperation with

[14] We note that this may make it more difficult to estimate the performance impact of such joint strategies with precision.

university or competitor cooperation. For large firms there is just one marginal significant impact found for a combination of supplier and university cooperation.

Looking at the other variables, we find that small firms' productivity growth benefits from incoming knowledge spillovers and investment expenditures, while no such evidence is found for large firms. Generally, large firms' productivity is much less sensitive to the adoption of R&D cooperation strategies but much more sensitive to own R&D expenditures. Past productivity has a much lower coefficient (-0.24) for large firms than for their smaller counterparts (-0.58), indicating that large firms maintain a substantial part of their productivity lead (76 percent), whereas a leading performance is much more difficult to sustain for smaller firms (only 42 percent).

The complementarity test results are presented in Table 6. For the full sample there are two statistically significant impacts: the pairs of competitor-customer cooperation and competitor-university cooperation. The results suggest that combining competitor and customer cooperation gives rise to complementarity in the innovation process and improves productivity. On the other hand, competitor and university cooperation are subadditive: when used simultaneously, they weaken productivity growth. This result is consistent with the suggestion by Leyden and Link (1999) that working simultaneously with a competitor and with public institutions may limit the appropriability of R&D efforts, as spillovers from universities may leak to non-collaborating competitors. Another possibility is that competitor cooperation may be geared towards incremental innovation and university cooperation towards radical innovation, which can be seen as diverging rather than converging objectives, increasing the complexity of R&D management (Mohnen and Hoareau, 2003).

The results confirm these effects if tests are performed for small firms only. In addition, two more sub-additive joint R&D cooperation strategies are present for small firms: cooperation with customers and suppliers, and cooperation with universities and suppliers, while customer and university cooperation are complementary. An intuitive explanation here is that cooperation with universities focuses on more radical types of product innovation, for which commercialization often requires customer collaboration to enhance acceptance and diffusion (Belderbos et al., 2004a; Tether 2002). On the other hand, supplier cooperation tends to focus more often on cost reduction and incremental process and product innovations, and this innovation strategy may be more difficult to combine with innovation efforts involving more radical objectives. These findings only hold for small firms, whilst for larger firms none of the combinations leads to significant performance effects. This is consistent with the notion that lack of management time and increased complexity of the innovation process may lead to underperformance of joint cooperation strategies in smaller firms. Larger firms on the other hand have more abundant resources and find it less problematic to handle multiple innovations objectives and management of multiple R&D collaborations.

Caveats and Alternative Specifications

It is useful to note a number of caveats in the above empirical exploration of complementarities in R&D cooperation strategies. First, although labor productivity is a rather comprehensive performance measure, on which R&D activities have a major impact, the results may still be dependent on the type of performance measure used. One may expect that innovation effort geared towards cost reduction has a more direct impact on productivity than do innovative efforts aimed at creation of entirely new products. The non-significant impact of university and customer cooperation as single cooperation strategies may hence be partly due to the choice of performance measure. If university and customer cooperation are more directed towards product innovations they may have a relatively greater impact on growth rather than on cost reductions and productivity increases.

Second, the insignificant results for large firms may be due to the imperfect (binary) measure of R&D cooperation strategies. Whereas for small firms a cooperative strategy is in most cases likely to involve a single collaborative effort, for larger firms the presence of R&D cooperation can hide substantial heterogeneity in the number and scale of such R&D collaborations. The fact that large firms adopt specific R&D cooperation strategies is much less informative of the firms' innovative efforts. Complexity issues are likely to arise within the group of collaborating firms as a function of the number of collaborative partners of a specific type, rather than in the combination of R&D partnerships of different types. Hence, we are inclined to consider our analysis as more representative for the sub-sample of smaller firms.

We estimated a number of alternative specifications of equation (4) to examine the robustness of the empirical results. We examined the possibility that the results are affected by reverse causality, if fast-growing firms have a greater propensity to engage in R&D alliances.[15] The empirical literature on the determinants of R&D cooperation has not provided evidence that firm growth or productivity differences affect the propensity to collaborate. Mohnen and Heaureau (2003) find no evidence that growth in employment has an effect on the propensity to cooperate in pooled data for four Western European countries. A "hiring personnel" variable was not significant in one of the first studies using Dutch CIS data (Kleinknecht and Reijnen, 1992). Fritsch and Lucas (2001) analyzing a large set of German firms find that the value-added-to-sales ratio has no positive effect on the propensity to engage in R&D cooperation. It is even possible that the most successful innovating firms are least likely to engage in R&D alliances because they are in a better position to go it alone and may face risks of knowledge dissipation.[16] Nevertheless, we investigated potential reverse causality by including past productivity growth (in the period 1995-1996, the year preceding the measurement of R&D collaboration) as an additional independent variable. The results from these models including past productivity growth were comparable to those presented in the paper, while the productivity variable itself was not significant. The results suggest that our empirical results do not under- or over-estimate the impact of R&D collaboration due potential reverse causality.

We also tried variables controlling for different objectives of firms' innovation strategies, with a potential impact on productivity growth. We distinguished "cost push" objectives (the importance of cost-saving objectives for innovation) and "demand pull" objectives (the importance of demand-enhancement objectives for innovation). These variables were not significant, and they did not affect the estimates of the other variables. We also estimated our model separately for manufacturing and services firms and performed the Chow test for the hypothesis that the coefficient vectors are not different for the two sectors. The Chow test statistic is 1.08 with (42, 1908) df, and, hence, we could not reject the hypothesis that the coefficient vectors are the same for the manufacturing and service firms in our sample.

[15] Generally, the literature has identified incoming spillovers as well as appropriability conditions as the most important determinants of R&D collaboration decisions (see, for example, Cassiman and Veugelers, 2002; Belderbos et al., 2004a).

[16] We thank the two referees for bringing up these points.

Finally, we examined different lags between R&D (cooperation) and productivity growth (e.g. Cincera et al., 2003). We found that the model with a 2-year lag (as presented in Table 5) had a substantially better fit than models with longer (3 and 4 year) lags, while no substantial differences in results were found. Models with longer lags may not accurately pick up the effects of the measured cooperation strategies, if during the 2-4 year period firms engage in (unmeasured) new collaborative agreements that have additional impacts on productivity growth. The shorter (2-year) lag between performance and R&D collaboration helps to avoid such 'contamination' due to later changes in R&D collaboration strategies.

6. Conclusions

In this paper we analyzed possible complementarities in cooperation strategies as they affect labor productivity growth for a large sample of innovating firms in two waves of the biannual Dutch Community Innovation Survey (1996, 1998). We distinguished four types of partner-specific innovation strategies: cooperation with competitors, customers, suppliers and universities and research institutes. We allowed for an appropriate time lag with which the impact of R&D cooperation (1996) feeds through in productivity growth (1996-1998) and applied a robust testing framework for complementarity between multiple practices based on multiple inequality constraints. This test indicates whether the impact of the adoption of one cooperative strategy significantly increases if another practice is adopted simultaneously. The results confirmed a positive impact overall of R&D cooperation on labor productivity growth, but with distinct differences in magnitude and significance of impacts depending on (combinations of) cooperation types. Competitor and supplier cooperation had the most direct positive impact on productivity growth. The empirical results on complementarities were mixed. Complementarity was found for joint cooperation strategies with competitors and customers, and with customers and universities. This is likely to be related to the role of customer cooperation in facilitating commercialization and quicker diffusion of product innovations that are due to competitor and university cooperation.

At the same time, a number of instances were found where the combination of cooperation strategies leads to underperformance: supplier cooperation combined with either university or competitor cooperation, and competitor cooperation combined with university cooperation. The former result may be explained by diverging objectives of different collaborative efforts: supplier cooperation tends to focus more often on cost reduction and incremental and process innovations, and this innovation strategy may be more difficult to combine with innovation efforts involving more radical product innovations associated with university and competitor collaboration. The combination of competitor and university collaboration may suffer from threats to appropriability of R&D efforts when working simultaneously with a competitor and public institutions, as spillovers from university may leak to competitors not involved in the collaboration (Leyden and Link, 1999).

These significant performance effects of combined cooperation strategies were found for small firms, while no significant impact was found for larger firms. On the one hand, this may be due to our inability to measure the actual importance of R&D partnerships for large firms as we could not measure the number and importance of different cooperation strategies. On the other hand, the differences between small and large firms is consistent with the notion that a lack of management time and the increased complexity of the innovation process is most likely to result in underperformance of joint cooperation strategies in small firms. In general the empirical results support such an 'increasing complexity' hypothesis and show a decreasing marginal impact of multiple cooperation strategies in particular when these imply multiple objectives.

The results of our analysis also raise a number of questions, which suggest pertinent issues for further research. Given the mixed findings on the benefits of pursuing multiple cooperation strategies simultaneously and the suggestion that complexity issues play a role here, a natural extension of analysis is to examine the impact of different cooperation strategies when adopted sequentially. This will require the construction of panel data, utilizing data from more than two innovation surveys. Other extensions concern the analysis of potential differences in the performance effects of R&D cooperation across industries, and the robustness of results for different performance measures than labor productivity.

A problem that is not easily solved is the lack of an indicator of the scale or number of R&D collaborations of each type in the European Community innovation survey data used here. To examine accurately the impact of R&D cooperation for larger firms, information on the number and importance of such partnerships may be indispensable. Here an alternative approach would be to utilize databases on R&D alliances that have been the subject of analysis in most of the management literature. Last but not least, empirical analysis in this area could greatly benefit from more theoretical work on combined R&D cooperation strategies and, in particular, the role of collaboration with partners other than competitors.

Table 1 Description of Variables

variable name	Definition
Competitor cooperation	1 if the business unit reported engagement in innovation in cooperation strategy with competitors, else zero
Supplier cooperation	1 if the business unit reported engagement in innovation in cooperation strategy with suppliers, else zero
Customer cooperation	1 if the business unit reported engagement in innovation in cooperation strategy with customers, else zero
University cooperation	1 if the business unit has reported engagement in innovation in cooperation strategy with universities, innovation centers, or research institutions, else zero
Incoming spillovers	Constructed as residual from the auxiliary regression of sum of scores of importance of university, competitor, and supplier spillovers taken from 1998 survey on a cooperation dummy taken from 1996 survey. In this way, we adjust the spillover variable from the influence of formal cooperation such that the estimated coefficients for R&D cooperation measure the full impact of R&D collaboration on productivity growth.
Investment intensity	Capital investment expenditures/sales
R&D intensity	Total innovation expenditures/sales
Firm size	Logarithm of the number of employees
Domestic group	1 if the business unit is part of a domestic firm grouping, else 0
Foreign multinational	1 if the firm is an affiliate of a foreign multinational, else 0
Merger	1 if the firm has acquired or merged with other firm(s) in the period 1994/1996, else 0.
Productivity growth (value added)	Growth in the net value added per employee = log (labor productivity 1998) – log (labor productivity 1996)

Note: all independent variables are for 1996 except for the spillover variables

Table 2 Means and Standard Deviations of Variables

	Mean	S.D.
Cooperation with:		
Competitors	0.021	0.142
Suppliers	0.047	0.212
Customers	0.038	0.191
Universities	0.020	0.140
Suppliers, universities	0.016	0.124
Customers, universities	0.015	0.122
Customers, suppliers	0.034	0.189
Customers, supplier and universities	0.020	0.140
Competitors, universities	0.013	0.114
Competitors and suppliers	0.007	0.080
Competitors and suppliers and universities	0.008	0.086
Competitors and Customers	0.008	0.088
Competitors and customers and universities	0.008	0.086
Competitors and customers and suppliers	0.013	0.114
Competitors, customers suppliers, universities	0.025	0.156
Log(value added per employee) in 1996	3.662	0.636
Investment intensity	0.020	0.053
Spillovers	0.008	4.667
Firm size	4.472	1.154
R&D intensity	0.007	0.019
Foreign MNE	0.205	0.404
Domestic group	0.271	0.445
# observations	1992	

Table 3. Distribution of firms across industries and R&D cooperation strategies

NACE	Sector	No. of obs. in sample	Share %	Share non-coop	No of obs	Share if COcoop=1	No of obs	Share if Scoop=1	No of obs	Share if CUcoop=1	No of obs	Share if Ucoop=1	No of obs
11,14	Mining	6	0.3	0.4	5	0.0	0	0.0	0	0.0	0	0.4	1
15,16	Food	128	6.4	6.3	89	6.7	14	7.9	27	6.7	22	10.8	27
17 – 19	Textile	51	2.6	2.7	38	2.9	6	2.6	9	2.1	7	3.2	8
21	Paper	59	3.0	2.7	38	3.9	8	4.7	16	3.6	12	5.2	13
22	Printing, publishing	67	3.4	3.8	54	1.5	3	2.3	8	1.2	4	0.8	2
23,24	Petroleum and chemicals	85	4.3	3.5	49	4.9	10	4.4	15	8.2	27	6.8	17
25	Rubber and plastic	74	3.7	3.2	46	4.9	10	4.4	15	5.8	19	3.2	8
27	Basic Metals	21	1.1	0.8	11	1.0	2	1.7	6	1.8	6	2.0	5
28	Metal products	146	7.3	7.3	103	5.9	12	8.2	28	7.9	26	7.2	18
29	Machines, equipment	170	8.5	9.6	134	3.9	8	5.2	18	6.4	21	5.2	13
30 - 33	Electronics	122	6.1	5.9	83	5.4	11	6.1	21	7.9	26	8.0	20
34,35	Cars and Transport	82	4.1	3.8	54	6.8	14	4.7	16	4.3	14	5.6	14
20,26,36,37	Other manufacturing	147	7.3	7.8	109	7.8	16	5.8	20	5.8	19	6.0	15
40,41	Utilities	22	1.1	0.8	11	2.9	6	1.5	5	1.2	4	2.8	7
45	Construction	131	6.6	7.4	104	5.9	12	4.4	15	2.1	7	5.6	14
50 - 55	Hotel, catering	359	18.0	18.1	255	16.2	33	19.8	68	17.0	56	10.4	26
60 - 64	Transportation, storage	82	4.1	4.6	64	3.4	7	3.2	11	4.3	14	0.8	2
70 - 74	Business services	212	10.6	9.8	137	14.7	30	11.4	39	11.8	39	14.5	36
90,93	Environmental, other services	28	1.4	1.4	19	1.0	2	1.7	6	1.8	6	1.2	3
Total		1992	100.0	100.0	1403	100.0	204	100.0	343	100.0	329	100.0	249

Table 4. Contingency table: Distribution of cooperation cases

Cooperation type	Number of cases	Number of cases small firms	Number of cases large firms
None	1403	909	494
Competitors	41	25	16
Customers	76	50	26
Supplier	94	35	59
University	40	14	26
Competitors and suppliers	13	7	6
Competitors and customers	16	10	6
Competitors and university	26	10	16
Customers and suppliers	74	31	43
Supplier and university	31	13	18
Customers and university	30	10	20
Competitors, customers, suppliers	26	12	14
Competitors, suppliers, university	15	3	12
Competitors, customers, university	17	3	14
Customers, suppliers and university	40	12	28
Competitors, customers, suppliers, universities	50	12	38
Total	1992	1156	836

Note: The R&D cooperation categories represent exclusive (combinations of) cooperation types: numbers represent the number of firms that are only engaged in the listed types of R&D partnerships.

Table 5. Estimates of Equation (3): determinants of firm productivity growth, 1996-1998

	(1) All firms	(2) Small firms	(3) Large firms
Log(productivity)96	-0.475*** (0.066)	-0.582*** (0.076)	-0.241 (0.037)***
Investment intensity	0.281*** (0.110)	0.309*** (0.108)	0.172 (0.384)
R&D intensity	1.853** (0.844)	0.217 (2.024)	2.829*** (0.586)
Incoming spillovers	0.006** (0.002)	0.006* (0.003)	0.001 (0.002)
Firm size	0.025** (0.016)	0.039* (0.040)	0.028 (0.018)
Foreign group	0.100*** (0.032)	0.127** (0.055)	0.074** (0.036)
Domestic group	0.034 (0.022)	0.036 (0.033)	0.040 (0.028)
Merger	-0.035 (0.026)	-0.058 (0.045)	-0.016 (0.027)
Industry dummies	YES	YES	YES
R&D Cooperation:			
Competitor	0.096** (0.044)	0.081 (0.058)	0.072 (0.076)
Customer	-0.041 (0.066)	0.002 (0.087)	-0.034 (0.048)
Supplier	0.057* (0.032)	0.142** (0.064)	0.010 (0.035)
University	0.016 (0.061)	0.155 (0.116)	-0.101 (0.068)
Competitor, supplier	0.250 (0.171)	0.519 (0.317)	0.020 (0.093)
Competitor, customer	0.215** (0.089)	0.256*** (0.086)	0.101 (0.152)
Competitor, university	0.080 (0.077)	-0.031 (0.112)	0.096 (0.096)
Supplier, customer	-0.004 (0.046)	-0.048 (0.077)	0.012 (0.052)
Supplier, university	0.108 (0.075)	-0.001 (0.070)	0.142* (0.083)
Customer, university	0.014 (0.073)	0.201** (0.097)	-0.141 (0.089)
Competitor, customer, supplier	0.140 (0.102)	0.150 (0.122)	0.155 (0.172)
Competitor, supplier, university	-0.004 (0.072)	-0.041 (0.091)	0.047 (0.103)
Competitor, customer, university	0.103* (0.064)	0.132 (0.218)	0.027 (0.056)
Customer, supplier, university	0.047 (0.058)	-0.068 (0.115)	0.017 (0.059)
Competitor, customer, supplier, university	0.069 (0.045)	0.088 (0.111)	0.000 (0.053)
Observations	1992	1156	836
R-squared	0.35	0.46	0.18
RSS	331.54	219.63	88.09
F(41, n={1950,1114,794})	25.88***	22.85***	4.23***

Robust standard errors in parentheses * significant at 10%; ** significant at 5%; *** significant at 1%. The Chow test (3.52) rejects no difference b/w large and small firms.

Table 6. Tests for complementarity and substitutability (subadditivity) between cooperation strategies

	All		Large firms		Small firms	
	Complements LR ≥	Substitutes LR ≤	Complements LR ≥	Substitutes LR ≤	Complements LR ≥	Substitutes LR ≤
					(3)	(4)
Competitors and Customers	8.799**	0.223	1.958	0.048	4.583	0.987
Competitors and Suppliers	0.897	4.611	0.003	6.951	4.501	0.117
Competitors and University	0	18.357***	1.199	3.179	0	12.817***
Customers and Suppliers	0.175	3.537	0.739	0.410	0	13.612***
Customers and University	2.701	0.705	0	3.804	6.964*	0.002
Suppliers and university	0.219	4.472	6.364	0.368	0.040	16.560***

Note: The reported LR statistics is for the test of the null hypothesis of the absence of complementarity (substitutability) for a given pair of strategies. The superscripts *, ** and *** indicate significance at 10%, 5% and 1% respectively. The log-likelihood values are given in the Appendix.

Appendix. Testing for complementarity and substitutability

This section describes the definition and conditions concerning complementarity and substitutability for the case of dichotomous practices. Consider an objective function *f(.)* of which the value is determined by the practices x_p (p=1,...,n). We use the following definition of complementarity (Milgrom and Roberts, 1990):

> *Practices x_1 and x_2 are considered complementary in the function f if and only if* $f(x_1+1, x_2+1, x_3,...,x_n) + f(x_1, x_2, x_3,...,x_n) \geq f(x_1+1, x_2, x_3,...,x_n) + f(x_1, x_2+1, x_3,...,x_n)$ *with the inequality holding strictly for at least one value of* $(x_1,...,x_n)$.

The definition for substitutability is identical to definition 1 except that the inequality is reversed.

The above definition can be more conveniently rewritten in terms of the possible combinations of practices. With two practices, the collection of possible combinations is defined in the usual binary order as $D = \{(0,0),(0,1),(1,0),(1,1)\}$. The set D has 16 elements when there are four practices, and the conditions of complementarity correspond to the four inequalities of type 1-a – 1-d discussed in section 3 of the paper.

The production function estimation is set up as a quadratic minimization problem subject to the Kuhn-Tucker restrictions. These inequality restrictions are imposed on the slope coefficients of the corresponding 15 'state' dummy variables, representing the exclusive combinations of four practices corresponding to equations 1-a – 1-d. Each equation is estimated in both restricted and unrestricted forms, and, subsequently, Wald and LR tests can be used to test the imposed inequality restrictions. In this paper, we use the LR test.

In the case of more than two practices, the number of inequality constraints that have to be tested simultaneously is 2^{n-2}. Statistical tests of $H_0: R\beta = r$ versus $H_a: R\beta \geq r$ with R having rank k in the standard linear model $y = X\beta + \varepsilon$ with one of the inequalities holding strictly have been considered in Gouriéroux, Holly, and Monfort (1982). Kudô (1963, p.414) derived the theorem underlying this test. From this theorem it follows that in the case of p inequality restrictions we have that the probability of LR exceeding c under the null hypothesis equals a mixed chi-square distribution of $\sum_{i=0}^{p} Pr\{\chi_i^2 \geq c\} w_{ip}$. The statistic can be compared to Table 1 from Kodde and Palm (1986) who provide critical values (c_l and c_u) for the significance levels ranging in size from 0.25 to 0.001 and degrees of freedom from 1 to 40.

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