

## INFRA-INDUSTRY SPILLOVERS AND R&D COOPERATION: THEORY AND EVIDENCE

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We analyse both the theoretical and the empirical side of the issue of R&D spillovers. Each firm's R&D costs are increasing in the amount of information transmitted to other firms, and we account for the possibility that firms control spillovers. We consider both Cournot-Nash and Cournot-Stackelberg behavior. The empirical analysis suggests that (i) firms' control on spillovers is relatively low; (ii) the cost-saving effect associated to joint ventures or R&D cartels is confirmed for industries where firms rely mainly upon own R&D as a source of innovation; (iii) R&D cooperation may increase information sharing, thereby enhancing spillovers.

*Keywords:* Spillovers; Joint venture; R&D cartel

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### 1 INTRODUCTION

Appropriability has long been identified as a major problem facing the innovating firm. For example, Jaffe (1986) found that for a firm with mean R&D the elasticity of patents with respect to other firms' R&D is about 1.1, which is consistent with a reasonable picture of R&D as a partial public good. Since it can hardly appropriate the benefits connected to its innovations, it is very likely that such firm will not perform the desired R&D projects, its possibility to fully exploit their results being threatened by rival firms. A solution to this dilemma is cooperative R&D, either conducted by firms who share the costs and benefits of particular R&D projects, or consisting in informal trading of proprietary know-how between rival firms (von Hippel, 1987; 1988).

A large empirical debate has unfolded over the last twenty years, concerning the magnitude of R&D spillovers (for an overview, see Geroski, 1995a,b; Griliches, 1995; *inter alia*). The overall appraisal maintains that technological externalities are widespread both inter- and intra-industry, although their magnitude varies considerably across industries.<sup>1</sup>

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<sup>1</sup>In particular, for inter-industry spillovers in R&D activities, see Bernstein and Nadiri (1998).

This discussion has triggered a corresponding theoretical approach to the analysis of R&D spillovers (see d'Aspremont and Jacquemin, 1988; Henriques, 1990; Katz and Ordover, 1990; de Bondt *et al.*, 1992; Kamien *et al.*, 1992; Suzumura, 1992), which conducts comparative statics upon equilibrium outputs and investments across alternative organizational designs such as R&D cartels and research joint ventures (RJVs) *vs.* noncooperative independent ventures. This analysis is carried out so as to point out whether arrangements like RJVs and R&D cartels may help firms overcome the wasteful effort duplication effect associated with strictly noncooperative behavior in the R&D phase.

However, in the aforementioned literature, technological externalities are considered as exogenous to firms. This assumption is arguable, in that RJVs and R&D cartels may indeed justify the idea that firms share their knowledge to a larger extent than they would in case of independent ventures. That is, any form of cooperation in R&D may allow firms not only to reduce individual as well as industry expenditures, but also to internalize externalities as much as possible through the endogenous manoeuvring of spillovers.

To our knowledge, the existing contributions exploring this issue are those of Katz (1986), Katsoulacos and Ulph (1998), Poyago-Theotoky (1999) and Piga and Poyago-Theotoky (2001).<sup>2</sup> In particular, Katsoulacos and Ulph (1998) evaluate the behavior of an RJV against independent ventures, to find that the spillovers associated with an RJV are at least as high as those associated with the alternative arrangement. On the contrary, a recent empirical contribution by Cassiman and Veugelers (2002) finds that the probability of cooperating in R&D is directly related to appropriability (*i.e.*, the probability increases with incoming spillovers and decreases with outgoing spillovers).

This paper attempts to link the theoretical and empirical strands of the literature on R&D spillovers by extending recent theoretical models of R&D spillovers and then testing some implications of those models using survey data on textiles, chemicals, and mechanical engineering in Europe. In particular, we analyze both the theoretical and the empirical side of the issues of information sharing, or technological externalities. The theoretical analysis is carried out along the approach introduced by Amir (2000), where each firm's R&D costs are increasing in the amount of information transmitted to other firms. We extend his analysis to account for the possibility that firms control spillovers, assuming that they decide on the extent of knowledge spillovers after the R&D investment. As a benchmark, we reassess the largely discussed case of a symmetric Cournot duopoly. Then, we investigate an asymmetric Cournot-Stackelberg duopoly where one firm is the leader at the market stage. The main results can be summarized as follows.

First, consider Cournot-Nash behavior at the marketing stage. A joint venture, being an organizational design meant to favor information sharing, involves larger spillovers than independent ventures. Then, there emerges that joint profit maximization at the R&D stage (R&D cartel) has a cost-saving effect as compared to noncooperative behavior if and only if spillovers are low enough. This entails that, if spillovers are endogenously controlled, independent ventures provide the right incentives towards cost saving.

Second, consider Cournot-Stackelberg behavior at the market stage. Here, we only examine strictly noncooperative behavior *w.r.t.* spillovers and R&D efforts. We find that (i) the leader's R&D investment is larger than the follower's if the spillover from the former towards the latter is sufficiently low; (ii) if firms completely control their respective spillovers, the leader invests less than under the Nash equilibrium solution, while the opposite holds for the market follower.

We test some of the implications of the theoretical analysis using a micro-aggregated version of the first Community Innovation Survey (CIS) database provided by Eurostat, in

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<sup>2</sup>A related paper by Kamien and Zang (2000) investigates the issue of absorptive capacity with exogenous spillovers.

relation to three industries (textiles, chemicals, and mechanical engineering) in manufacturing for five European countries: Belgium, Denmark, Germany, Italy, and Norway. Concentration is measured by the Linda index.

The remainder of the paper is structured as follows. The theoretical analysis is carried out in Section 2. The data set is described in Section 3. Section 4 contains the exposition of empirical results. Finally, concluding remarks are in Section 5.

## 2 THE THEORETICAL SETUP

### 2.1 A Duopoly Model with Spillovers

We borrow the theoretical framework from Amir (2000, see also Hinloopen, 2001). We consider a duopoly where quantity-setting firms supply homogeneous products, market demand being

$$p = a - q_1 - q_2. \quad (1)$$

Firm  $i$ 's constant marginal cost is given by  $c_i = c - x_i - \beta_j x_j$ , where  $x_i$  is the R&D investment of firm  $i$  in cost reducing activities, and parameter  $\beta_j \in [0, 1]$  measures the amount of spillover from firm  $j$  to firm  $i$ . The R&D cost function of each firm is  $K_i(x_i) = (1/2)\gamma(1 + \beta_i)x_i^2$ . Observe that the spillover to firm  $j$  enters the cost function of firm  $i$  so as to make it costly to the latter to transmit knowledge to the rival.<sup>3</sup> The profit function looks as follows:

$$\pi_i = (a - q_i - q_j - c + x_i + \beta_j x_j)q_i - \frac{\gamma}{2}(1 + \beta_i)x_i^2. \quad (2)$$

As shown by Amir (2000; see also Hinloopen, 2001, for computational details), this setting encompasses both d'Aspremont and Jacquemin (1988) and Kamien *et al.* (1992).<sup>4</sup>

We will examine the following cases:

- A symmetric duopoly where  $x_i$  and  $q_i$  are both set simultaneously, with  $x_i$  being chosen either cooperatively or noncooperatively, while  $q_i$  is always set noncooperatively.<sup>5</sup> This case is a simple extension of Amir's (2000) setup to allow for endogenous spillovers. It is sketched out in some detail to safeguard the consistency and readability of the remainder of the paper.
- An asymmetric duopoly with a dominant firm at the market stage. Here, R&D efforts are chosen simultaneously and noncooperatively, while the market stage is played *à la* Stackelberg.

In both cases, we will investigate the bearings on firms' performance as well as on social welfare of joint *vs.* independent ventures. By this we mean that we are going to model explicitly firms' choices concerning the size of spillover  $\beta_i$ . Notice that the profit function (2) of firm  $i$  is, respectively, linear and increasing in  $\beta_j$ , and linear and decreasing in  $\beta_i$ . This makes it possible to establish that it is in the interest of each firm to set  $\beta_i = 0$  (respectively,  $\beta_i = 1$ )

<sup>3</sup>In Amir (2000), symmetric spillovers are considered from the outset, so that the R&D cost function is  $K_i(x_i) = (1/2)\gamma(1 + \beta)x_i^2$ . Alternatively, spillover effects may materialise under product innovation, via the demand functions (see Lambertini and Rossini, 1998; Lambertini *et al.*, 1998; 2002; 2003).

<sup>4</sup>For the strategic relevance of endogenous spillovers in R&D races, see De Fraja (1993).

<sup>5</sup>The possibility that firms cooperate at the market stage is considered both in d'Aspremont and Jacquemin (1988) and in Amir (2000). We say "cooperate" rather than "collude" because cartel stability is not characterised in either of these papers.

if firms choose independent ventures (resp., if the set up a joint venture).<sup>6</sup> The structure of the three-stage game we are about to examine is the following:

*Stage 1* Firms choose investment levels  $x_i$ , either noncooperatively or cooperatively (if they are participating in an R&D cartel).

*Stage 2* Given the decisions taken at Stage 1, firms optimally set the value of  $\beta_i \in [0,1]$ , by which firms decide how much of the knowledge generated by the subsequent R&D activity they want to share (or not to share).

*Stage 3* Firms compete in output levels, either simultaneously or sequentially.

As usual, the solution concept is the subgame perfect equilibrium by backward induction.

## 2.2 Cournot-Nash Competition

We consider here the case where the market stage is played simultaneously. Proceeding by backward induction, the market stage is solved first for given values of  $x_i$  and  $\beta_i$ . From the first order conditions (FOCs), we obtain the Cournot-Nash equilibrium quantity of firm  $i$ :

$$q_i^N = \frac{a - c + (2 - \beta_i)x_i - (1 - 2\beta_j)x_j}{3} \quad (3)$$

Plugging (3) into the profit functions (2) and simplifying, one gets the relevant objective function of firm  $i$  at the second stage of the game:

$$\pi_i = \frac{[a - c + (2 - \beta_i)x_i - (1 - 2\beta_j)x_j]^2}{9} - \frac{\gamma(1 + \beta_i)x_i^2}{2} \quad (4)$$

Suppose first that firms can perfectly control the reciprocal spillover effects, as in Poyago-Theotoky (1999).<sup>7</sup> Observe that  $\pi_i$  is parabolic and convex in  $\beta_i$ . In particular,  $\partial^2 \pi_i / \partial \beta_i^2 = 2x_i^2/9 > 0$  for all admissible levels of the firm's R&D effort.<sup>8</sup> Hence, we can only expect corner solutions in the second stage, where firms decide over the extent of the reciprocal spillovers. This leads to the solution of the second stage:

LEMMA 1 *Assume firms can perfectly control the reciprocal spillovers. If so, firms' choices as to their reciprocal spillovers are as follows:*

- (i) *Independent Ventures. When firms do not cooperate in terms of information sharing, then  $\beta_i = 0 \forall i$ .*
- (ii) *Joint Venture. If firms set up a joint venture at the second stage, then  $\beta_i = 1 \forall i$ .*

Consider now the first stage, where firms decide upon their R&D efforts  $x_i$ . In order to convey some additional information on the interplay between spillovers and R&D commitments,

<sup>6</sup>What we define here as a joint venture is elsewhere called information sharing (see, e.g., Sasaki (2003)). The endogenous formation (and the optimal size) of coalitions, i.e., R&D joint ventures, is investigated by Yi and Shin (2000) in a model with  $n$  firms.

<sup>7</sup>Piga and Poyago-Theotoky (2001) consider an R&D game for process innovation, where spillovers are inversely related to the degree of horizontal differentiation, so that minimum differentiation produces the maximum amount of technological externality.

<sup>8</sup>Poyago-Theotoky (1999) assumes that the costs of innovation are  $(\gamma x_i^2)/2$ . However, this does not affect the sign of  $\partial \pi_i / \partial \beta_i$ , which is always negative.

all equilibrium expressions of  $x_i$  are first derived for generic values of  $\beta_i$ , as in Amir (2000). To start, examine the situation where firms noncooperatively choose investment levels.

**2.2.1 Noncooperative R&D Activities**

If firms activate independent ventures, behaving noncooperatively in both stages, the following holds:

*Remark 1* If the R&D cost parameter  $\gamma \in (2/9, 4/9)$ , firms may activate a joint venture (with  $\beta_i = \beta_j = 1$ ) while they cannot choose independent ventures (with  $\beta_i = \beta_j = 0$ ).

*Proof* See Appendix.

Remark 1 states that, when spillovers are endogenous, a joint venture widens the cost parameter region wherein an internal solution to the R&D stage exists. That is, the admissible region of  $\gamma$  where firms invest positive amounts of resources in their R&D activities becomes larger under a joint venture as compared to independent ventures, precisely because firms control the level of the reciprocal technological externality.

**2.2.2 R&D Cartel**

Consider now the case of joint profit maximization in the R&D effort levels, while output levels are determined noncooperatively in the second stage. The following result emerges (cf. Amir, 2000, Appendix):

LEMMA 2 Compare the R&D effort levels  $x^N$  and  $x^C$ . For generic spillover levels, we have that

$$\text{sign} \{x^N - x^C\} = \text{sign} \left\{ \frac{2\beta - 1}{(2 + 2\beta - 9\gamma)(2\beta + 9\gamma - 4)} \right\}.$$

*Proof* See Appendix.

This yields a number of interesting although scarcely intelligible subcases. If firms optimally control their reciprocal spillovers in the second stage, the following holds:

PROPOSITION 1 Suppose firms control technological spillovers, and compare the R&D effort levels  $x^N$  and  $x^C$ :

- (i) Under independent ventures, set  $\beta = 0$  and assume  $\gamma > 4/9$  in order for  $x^N(JV)$  and  $x^C(JV)$  to be both admissible. Then,  $x^N(JV) > x^C(JV)$ .
- (ii) Under joint venture, set  $\beta = 1$  and assume  $\gamma > 2/9$  in order for  $x^N(IV)$  and  $x^C(IV)$  to be both admissible. Then,  $x^N(IV) < x^C(IV)$ .

Of course we are not claiming that a situation where  $\beta = 0$  or  $\beta = 1$  is necessarily descriptive of real-world cases, in that typically firms cannot expect to perfectly master information transmission or leakage. However, Proposition 1 presents a stylized picture which can be thought of as the benchmark of perfect spillover control that firms' real behavior should approximately reproduce.

A firm's individual preferences over the alternative arrangements for innovative activities are summarized by:

PROPOSITION 2  $\pi^C(JV) > \pi^N(JV) > \pi^C(IV) > \pi^N(IV)$  for all  $\gamma > 4/9$ .

Proposition 2 establishes that, overall, the joint venture clearly dominates independent ventures from the individual firm's viewpoint. Instead, the convenience of cooperation at the first stage is ambiguous, in that the choice of noncooperative research efforts dominates cooperation if the former perspective is accompanied by a joint venture while the second combines with independent ventures. Observe that the chain of inequalities in the above proposition fails to hold if  $\gamma \in (2/9, 4/9)$ , where only independent ventures are admissible while the joint venture is not.

Social preferences remain to evaluate. This is done in the following:<sup>9</sup>

PROPOSITION 3  $SW^C(JV) > SW^N(IV) > SW^N(JV) > SW^C(IV)$  for all  $\gamma > 4/9$ .

Finally, Propositions 2 and 3 produce the following relevant corollary:

COROLLARY 1 *The combination of R&D cooperation and joint venture appears as the best option from both the individual and the social standpoint.*

### 2.3 Cournot-Stackelberg Competition

Here, we characterize the situation where there exists a dominant firm. To formalize this idea, we suppose that one firm takes the lead at the third stage of the game, and the rival follows. As in Section 2.1.1, the solution concept for the first and the second stage is the simultaneous Nash equilibrium. Although, in line of principle, an R&D cartel could also be considered, this would entail several difficulties with the distribution of profits among cartel members, as profits could be shared (i) on equal bases, (ii) according to a Nash bargaining solution, or (iii) proportionally to the asymmetric firms' market shares.

In this setting, we obtain the following:

PROPOSITION 4 *When the market stage is a Stackelberg game, then*

- (i) *If spillovers are exogenous or imperfectly controlled by firms, the market leader invests more than the follower if the spillover from the leader to the follower is sufficiently low.*
- (ii) *If firms control their respective spillover levels, the market leader invests less than under the Nash equilibrium solution for all admissible values of the relevant parameters. The opposite holds for the market follower.*

*Proof* See Appendix.

Now suppose firms control spillovers. Evaluating the overall effort of the industry under the Stackelberg solution, against the corresponding magnitude observed under the Nash solution, we obtain the following.

<sup>9</sup>The detailed proof is omitted as it simply requires the computation of consumer surplus in the cases under consideration, using the demand function (1).

**PROPOSITION 5** *If spillovers are entirely endogenous, industry R&D effort is larger under the Nash equilibrium than under the Stackelberg equilibrium for all  $\gamma > 2$ .*

This can be entirely imputed to the lower incentive for the leader to invest in process innovation, due to the fact that this firm trades off the possibility of enhancing her own profits through market leadership against the alternative consisting in a costly commitment. Observe that the above statement is true *a fortiori* when  $\gamma \in (0, 2]$ , as in such a range the Stackelberg equilibrium is inadmissible. Moreover, it is worth stressing that an analogous to Proposition 5 also holds when firms control their reciprocal externalities though only imperfectly. Therefore Proposition 5, although presenting an extreme situation, is descriptive of a rather wide range of cases.

## 2.4 Discussion

The above analysis has been carried out under the assumption that technological spillovers are entirely under the firms' control. Namely, by assuming that  $\beta$  is somewhat equivalent to the design of organization: in the case of independent ventures, there are no spillover ( $\beta$  equals zero); when firms form research joint ventures, there is complete spillover ( $\beta$  equals unity). However, in real-world situations we may not expect firms to be able to perform such a complete mastering of the flow of information produced by their R&D activities. For example, illegal information acquisition and/or skilled labor mobility may generate some degree of spillovers escaping firms' control. Thus, we can extend the characterization of the Cournot setting by considering Propositions 6 and 7, which provide some additional hints for the empirical analysis.

**PROPOSITION 6** (Amir, 2000) *Suppose spillovers are uncontrollable by firms. Then, for all values of  $\gamma$  such that  $x^N, x^C > 0$ , we have:*

- (i)  $x^N > x^C$  for all  $\beta \in [0, 1/2)$ , and
- (ii)  $x^N < x^C$  for all  $\beta \in (1/2, 1]$ .

*Proof* To prove the above claim for the case where firms behave *à la* Cournot-Nash in the market stage, it suffices to compare (6) against (8), provided that the value of  $\gamma$  is such that both  $x^N$  and  $x^C$  are positive.

This amounts to saying that cooperation in R&D entails an effort-saving effect if and only if technological spillovers are low enough. In the opposite case, cooperation produces higher R&D efforts as compared to the noncooperative setting, because the maximization of joint profits allows firms to extract more consumer surplus and thus leads them to invest a larger amount of resources (see also d'Aspremont and Jacquemin, 1988; Kamien *et al.*, 1992; Suzumura, 1992). However, this result drastically depends upon firms' ability to control endogenously the extent of externalities. In general, the following holds:

**PROPOSITION 7** *Since  $\partial\Pi^C/\partial\beta_i > 0$  and  $\partial\pi_i^J/\partial\beta_i < 0$ ,  $J = N, SF, SL$ , spillovers can be expected to be higher when firms set up an R&D cartel, as compared to all other situations where they compete in R&D.*

The above statement is a qualitative prediction suggesting that cooperation may boost the exchange of information between firms (and conversely for the case of noncooperative behavior). The intuition behind it is that, by activating a cartel, firms may better internalise the benefits of R&D activity. This holds by definition, since the R&D investment in such a case is designed to maximise joint profits. *A fortiori*, the same must be true if firms control

spillovers (or information sharing). On the contrary, competing firms would limit as much as possible the externality (or information leakage) to rivals. If such control is complete, then we have the following Corollary to Propositions 6 and 7.

**COROLLARY 2** *If firms fully control their reciprocal spillovers, then the R&D cartel allows firms to spend 50% less than they would under noncooperative behavior.*

*Proof* To prove this result, one has to plug, respectively,  $\beta = 0$  in (6) and  $\beta = 1$  in (8), obtaining:

$$x^N = \frac{4(a-c)}{9\gamma-4}; \quad x^C = \frac{2(a-c)}{9\gamma-4}.$$

### 3 DATA AND VARIABLES

In order to provide empirical evidence in support of some of the theoretical hypotheses discussed in previous sections, we use a micro-aggregated version of the first Community Innovation Survey (CIS) database provided by Eurostat. The CIS project was launched in 1991 to store micro data on innovative activities from all member countries of the European Union (EU) and other European countries (including Norway) in one common, harmonized data base. As a firm-based survey of innovation, it provides information on innovative output, determinants of innovation, barriers to innovation, innovative efforts, and innovative results (Brouwer and Kleinknecht, 1999; Lotti and Santarelli, 2001). In this connection, it can be used to overcome the most frequent problems arising from the adoption of traditional indirect measures of innovation, such as R&D investments, number of patents, and technological balance of payments, which often underestimate the innovative performance of small and medium sized firms. Three surveys have been carried out to date, each of which provides information which can be used for international comparisons at the sectorial level (for a survey, cf. Hinloopen, 2003).

We use only the first CIS, in consideration of the nature of the micro level data made available from Eurostat in relation to such survey, offering some interesting hints also from a strictly statistical viewpoint. In fact, due to confidentiality reasons, the original data collected for year 1992 in each of the participating countries were micro-aggregated by Eurostat using different techniques according to the nature of the variables. Three micro-aggregation procedures were applied in the cases of quantitative, ordinal, and nominal variables, respectively: individual ranking, individual ranking with “snake”, and classification by “similitude”. Application of the individual ranking method to quantitative variables required the primary variables to be ranked in increasing order, and individual observations to be grouped by three and then replaced with the cluster arithmetic mean. Whereas all the metric variables were micro-aggregated independently, ordinal variables were grouped into appropriate segments, and then ranked accordingly. In particular, once a segment of at least two ordinal variables had been identified, an arbitrary aggregation path (the snake) was chosen. The first three observations that the snake encountered were grouped together and therefore the original values were replaced with the median of the group. Then, the same procedure applied to the next three and so on. In the case of nominal variables, a simple method of grouping similar observations according to a particular segment was used: the most similar three observations were grouped together and the original values replaced by the cluster mode.<sup>10</sup>

<sup>10</sup>It is worth noting that the observations grouped together had a very close distribution.

TABLE I Number of (Pseudo) Firms by Industry and Country.

	<i>Textiles</i>	<i>Chemicals</i>	<i>Mech. Eng.</i>	<i>Total</i>
BEL	498	327	326	1151
DK	69	106	349	524
GER	2092	2350	10,589	15,031
ITL	919	552	1969	3440
NOR	12	34	117	163
Total	3590	3369	13,350	20,309

Thus, in the present paper, we use micro-data dealing with “pseudofirms” obtained through a standardized micro-aggregation procedure. In particular, the CIS database is employed in relation to three industries in manufacturing for five European countries, four of which, namely Belgium, Denmark, Germany and Italy are EU members, whereas one, Norway, is not. The three industries were selected on the basis of their general technological features, according to the commonly used taxonomy suggested by Pavitt (1984). We chose the following types of industries: *supplier dominated* (Textiles<sup>11</sup>), *science based* (Chemicals), and *specialized suppliers* (Mechanical engineering). As far as the variables are concerned, all the relevant information refers to 1992, with the monetary values expressed in current 1992 ECU. In detail, the following variables are used:

1. R&D = current R&D expenditures;
2. R&D\_empl = current R&D expenditures per employee (as a proxy of R&D intensity);
3. Amount of Spillovers = R&D expenditures/total sales times the sum of other firms’ R&D (as in Jaffe, 1986);<sup>12</sup>
4. R&D\_CoopYES/NO = denotes whether the (pseudo)firm is/is not involved in any kind of formal or informal R&D cooperation (information sharing) with other (pseudo)firms.

For the sake of completeness, we base the empirical test of the theory developed in previous sections alternatively on level of expenditure or intensity of R&D, since they often give different results.

The distribution of (pseudo)firms by industry and country is reported in Table I.

The original survey was carried out on a sample of enterprises, representative of the whole frame population. Accordingly, before carrying out any analysis, it was necessary to take into account the grossing up factors (or weighting factors). To this purpose, each observation was multiplied for the corresponding weighting factor.<sup>13</sup>

#### 4 EMPIRICAL RESULTS

Due to strong data constraints, we could only test directly Propositions 4, 5, 6 and 7. As a consequence, Propositions 1, 2 and 3 developed in Section 2.2 in relation to

<sup>11</sup>Although certain portions of the textile industry are likely to be *scale intensive* in the sense of Pavitt.

<sup>12</sup>The underlying hypothesis is therefore that the R&D productivity of each firm is increased by the R&D of its “technological neighbors”, *i.e.* firms belonging to the same industry and country. In computing this variable, we take into account the R&D “pool” of a firm, *i.e.*, the sum of the R&D expenditures of all the other firms in the industry. The main difference with Jaffe (1986) is that our data do not allow the R&D “pool” to be weighted by the technological distance.

<sup>13</sup>Estimations carried without weighting factors provide results consistent with those presented here. They are available from the authors upon request.

Cournot-Nash equilibrium have implications only for the completion of the theoretical reasoning carried out in the first part of the paper.

As stated in Propositions 4 and 5, Stackelberg leaders are expected to have a lower innovative effort than other firms. For the purposes of the empirical analysis, we identified Stackelberg leaders by computing for each industry in each country a particular measure of concentration: the Linda (1993) index.<sup>14</sup> This index differs from the most commonly used measures of concentration and, in spite of its weakness in defining the boundaries of the market, can be usefully employed in identification of the “oligopoly threshold”. Firms inside the oligopoly area are taken as Stackelberg leaders, whereas those outside are considered as Stackelberg followers. In the present paper, we compute market shares as ratios between a (pseudo)firm’s sales and total sales in the industry. We do this separately for each national market, since no evidence is forthcoming from preliminary inspection of the data that the (pseudo)firms included in the analysis are competing in the whole trans-national market defined by the five countries taken into account.

A summary of the results is presented in Table II. The emergence of a large number of leaders from the tests in relation to two industries (Textiles and Chemicals) for Germany and one (Textiles) for Belgium can be given the following explanation. On the one hand, from Ono (1982) and Albaek (1990), we know that cost asymmetry or uncertainty yield the Stackelberg equilibrium as the natural solution to market games. On the other hand, cost asymmetry is in itself sufficient (even in the absence of sequential play) to ensure that the most efficient firm has a dominant market position which is observationally similar to that of a proper Stackelberg leader. Therefore, we may well expect the data to answer positively to a test for leadership in both cases, yielding thus a picture where the number of leaders is large, even though some of those firms are simply more efficient than rivals and do not enjoy a leadership in the Stackelberg sense. Furthermore, from a strictly empirical viewpoint, one cannot help but note that in the case of Italy, where all industries are dominated by small and micro firms with a scanty significant market share, no leaders are found for any of the three industries.

To test propositions 4 and 5 empirically, we use (Tab. III) a simple analysis of variance (ANOVA) test for the differences in the mean values of R&D effort between two groups of (pseudo)firms: alleged Stackelberg leaders and alleged Stackelberg followers. In particular,

TABLE II Number of Market Leaders by Country and Industry.

	<i>Belgium</i>	<i>Denmark</i>	<i>Germany</i>	<i>Italy</i>	<i>Norway</i>	<i>Total</i>
Textiles	132	23	418	0	5	578
Chemicals	15	34	496	0	4	549
Mechanical Eng.	7	7	0	0	23	37

<sup>14</sup>This index is based on the following relation:

$$Q_i = \frac{A_i/i}{(A_K - A_i)/(K - i)},$$

where firms are ordered by the decreasing value of their market share  $Q_i$ , with  $A_i$  denoting the total market share of the first  $i$  firms among the  $K$  largest ones. In this relation,  $K$  is a number bounded between 2 and  $N$ , which in turn denotes the total number of firms. The Linda index is then computed as:

$$L = \frac{1}{K(K-1)} \sum_{i=1}^{K-1} Q_i.$$

In this way, a measure of concentration ( $L$ ) obtains, conditional upon the (arbitrary) value chosen for  $K$ . Accordingly, in order to identify the oligopoly threshold (if it does exist) in each market, a set of Linda indices must be computed:  $L_2$  for  $K = 2$ ,  $L_3$  for  $K = 3$ ,  $L_4$  for  $K = 4$ , and so on. When it is identified, the first discontinuity in the computed values of the Linda index denotes the subset of firms operating in the oligopoly area.

TABLE III Empirical Test of Propositions 4 and 5. Market leaders have a lower incentive to invest in R&amp;D.

	<i>Type of firms</i>	<i>Mean</i>	<i>Std Dev</i>	<i>N. cases</i>	<i>ANOVA</i>
Text.					
R&D	All	127.520	990.0780	3590	
	Followers	70.3158	298.7992	3012	63.5842*
	Leaders	425.8570	2351.5280	577	
R&D_EMPL	All	1.4664	2.9249	3590	
	Followers	1.2552	2.3163	3012	100.2746*
	Leaders	2.5677	4.8769	577	
Chem.					
R&D	All	3751.8390	36262.7565	3339	
	Followers	1062.7658	6612.8472	2790	95.8840*
	Leaders	17406.3445	86939.2089	549	
R&D_EMPL	All	15.2206	178.4924	3339	
	Followers	17.0658	195.2102	2790	1.8124
	Leaders	5.8510	6.5240	549	
Mech. Eng.					
R&D	All	681.6399	4867.5209	13,350	
	Followers	661.0321	4790.4473	13,313	86.9880*
	Leaders	8125.0784	15607.2925	37	
R&D_EMPL	All	7.7654	105.7435	13,348	
	Followers	7.7740	105.8893	13,311	0.0319
	Leaders	4.6591	5.8409	37	

\*Significant at 99% level of confidence.

we tested the level of significance of such differences using as measures of R&D effort both the total amount of firms' R&D expenditures and the current R&D expenditures per employee.

With the first measure of innovative activity, that is also the weakest, the result predicted by the theory is rejected in all industries: Stackelberg leaders invest in R&D more than Stackelberg followers. This may suggest that the extent, if any, to which firms control spillovers is relatively low. More controversial findings are found when using the most reliable measure for R&D intensity: indeed, for both chemicals and mechanical engineering – namely, the two industries that, according to their general technological features, are likely to be more clearly committed to own R&D – it turns out that Stackelberg leaders invest in R&D less than Stackelberg followers, but the differences in the mean values are not statistically significant. These results can be taken as a partial corroboration of the hypothesis presented in Propositions 4 and 5 above.

As stated in Proposition 6(ii), firms involved in R&D cooperation are expected to exhibit higher levels of R&D investment. To test this theoretical prediction empirically, we employ again the ANOVA test for the differences in the mean values of R&D effort in the cases of (pseudo)firms who are involved in R&D cooperation and (pseudo)firms who are not.

Concerning the case of textiles<sup>15</sup> (Tab. IV), the empirical test supports the hypothesis that firms involved in R&D cooperation display a higher level of R&D effort, in terms of both R&D expenditures and R&D intensity. This finding is consistent with the results by Lotti and Santarelli (2001) and Sterlacchini (1998), showing that since the early 1990s even firms belonging to traditional consumer goods industries started to undertake autonomous innovative activities and to introduce R&D labs.

<sup>15</sup>Even if, in the case of R&D expenditures, the difference is not statistically significant.

TABLE IV Empirical Test of Propositions 6 and Corollary 8. R&amp;D cooperation leads to higher R&amp;D investments.

	<i>Type of firms</i>	<i>Mean</i>	<i>Std Dev</i>	<i>N. cases</i>	<i>ANOVA</i>
Text.					
R&D	All	127.5120	990.0786	3590	0.0122*
	R&DCoop NO	126.7517	1070.9732	3059	
	R&DCoop YES	131.8924	141.9000	531	
R&D_EMPL	All	1.4664	2.9249	3590	428.52906*
	R&DCoop NO	1.0684	2.8235	3059	
	R&DCoop YES	3.7591	2.3991	531	
Chem.					
R&D	All	3751.8367	36262.7403	3339	9.1226*
	R&DCoop NO	2979.6535	37059.6263	2863	
	R&DCoop YES	8393.2415	30671.6717	476	
R&D_EMPL	All	15.2206	178.4925	3339	0.5575
	R&DCoop NO	16.1614	192.7407	2863	
	R&DCoop YES	9.5656	6.3467	476	
Mech. Eng.					
R&D	All	681.6399	4867.5209	13,350	78.9763*
	R&DCoop NO	540.5371	4148.4142	11,681	
	R&DCoop YES	1669.2057	8245.7182	1669	
R&D_EMPL	All	7.7654	105.7435	13,348	0.4777
	R&DCoop NO	8.0046	112.9907	11,679	
	R&DCoop YES	6.0919	9.2985	1669	

\*Significant at 99% level of confidence.

With respect to chemicals and mechanical engineering, the differences in R&D intensity between firms who are involved in cooperative R&D and firms who are not are instead not statistically significant, whereas R&D expenditures are significantly higher for cooperating firms. This result confirms the hypothesis put forward by Weitzman (1998) in his attempt to provide new microfoundations for the knowledge production function: knowledge builds upon itself in a combinatoric feedback process. This implies production of new ideas to be a function of newly reconfigured old ideas, through a cumulative process in which R&D cooperation and spillovers enhance the likelihood of obtaining innovations.

Given the specific features of the overall innovation process in each industry, the results emerging from the *supplier dominated* (Textile) industry<sup>16</sup> suggest that when own R&D is not as relevant as other sources of technological inputs (*e.g.*, knowledge embodied in new machinery and technical equipment, acquisition of information relevant to innovation projects from clients and/or suppliers, learning by doing, etc.), cooperative R&D is a way to enhance the commitment, and improve the ability, to carry out own R&D. It might be argued whether R&D cooperation may substitute or enhance own R&D effort. Besides, this industry borrows its technological inputs from upstream industries and specifically from the mechanical engineering industry, which can be seen as the source of spillovers for downstream users. Thus, a distinction between vertical (from outside the industry) and horizontal (from within the industry) spillovers applies in general to the case of *supplier dominated* industries.

In our empirical analysis we test the hypothesis that R&D cooperation has a cost saving effect in industries in which R&D is the major source of innovation. It is however likely that in absence of cooperation such firms could not have reached comparable levels of innovative activity, thereby suggesting the presence of a substitution effect. Yet, due to the lack of

<sup>16</sup>Which have been shown by Pavitt (1984) to rely almost exclusively on external sources of innovation.

TABLE V Empirical Test of Proposition 7. Cooperation enhances the level of R&amp;D spillovers.

<i>Amount of spillovers</i>	<i>Type of firms</i>	<i>Mean</i>	<i>Std Dev</i>	<i>N. cases</i>	<i>ANOVA</i>
Text.	All	10.5100	0.5760	3590	31.9180*
	R&DCoop NO	10.5325	0.6072	3059	
	R&DCoop YES	10.3802	0.3157	531	
Chem.	All	14.2883	0.5807	3339	29.3018*
	R&DCoop NO	14.2662	0.5793	2863	
	R&DCoop YES	14.4211	0.05719	476	
Mech. Eng.	All	13.8600	0.5685	13,350	41.8309*
	R&DCoop NO	13.8480	0.5714	11,681	
	R&DCoop YES	13.9441	0.5402	1669	

\*Significant at 99% level of confidence.

lagged variables, we could not carry out any causality test. In terms of Corollary 8, the theoretical model suggests that cooperating firms may use spillovers as a substitute for direct investment in R&D, thereby saving on industry R&D efforts as compared to the noncooperative setting. In this respect, the answer from our empirical tests is negative, as it appears that firms cannot control reciprocal spillovers enough to reduce cooperative R&D expenditure.

Conversely, in industries which rely mostly (although not exclusively) upon own R&D as a source of innovation, like chemicals and mechanical engineering, rival firms are more likely to be involved in formal and informal trading of proprietary know-how.

In Proposition 7 above, we assert that involvement in R&D cooperation may boost the exchange of information between firms, thereby enhancing the level of R&D spillovers. According to the results shown in Table V – again obtained by running the ANOVA test for the differences in the mean values of R&D expenditures over total sales times the R&D investment of all other firms (Jaffe, 1986) – Proposition 7 is confirmed in two industries out of three: with the sole exception of the textile industry,<sup>17</sup> (pseudo)firms involved in R&D cooperation benefit from a higher level of spillovers.

## 5 CONCLUDING REMARKS

In this paper, we attempted to link the theoretical and empirical strands of the literature on R&D spillovers by testing some implications of recent theoretical models aptly extended to take into account real-world situations. In this connection, we have investigated several aspects of firms' R&D activity, under the assumption that quantity-setting firms may control technological externalities. We have considered both Cournot-Nash and Cournot-Stackelberg behavior. Under Cournot-Nash behavior at the market stage, we have addressed an issue that has been largely debated in the existing literature, namely, whether cooperation (either as a joint venture or as an R&D cartel) entails a reduction in the well known effort duplication effect associated with strictly noncooperative behavior. Under Cournot-Stackelberg behavior, we have investigated the incentives to invest in R&D when firms are asymmetric.

Our findings can be summarized as follows. First, the empirical investigation suggests that the extent to which firms endogenously control spillovers is relatively low. Second, for textiles the empirical test supports the claim that R&D cooperation entails a higher level of R&D effort. This result cannot be confirmed for chemicals and mechanical engineering, since in

<sup>17</sup>Although their differences are statistically significant, the absolute levels of the mean values are very close to each other.

the case of such industries the differences in R&D intensity between firms who are involved in cooperative R&D and firms who are not statistically significant. The results obtained for the *supplier dominated* (Textile) industry suggest that when own R&D is not as relevant as other (in this case external) sources of technological improvement, cooperating in R&D may enhance the commitment, and improve the ability, to carry out own R&D. Third, in the case of the most technologically advanced industries (chemicals and mechanical engineering) the tests confirm that R&D cooperation may increase information exchange between firms, thereby enhancing spillovers.

Therefore, the empirical analysis does not provide full support to the idea that firms control spillovers, and this finding is of particular importance in those industries (such as textiles in our analysis) in which vertical spillovers from upstream producers matter even more than horizontal ones. Indeed, it appears that spillovers are an environmental feature conditioning firms' efforts, rather than the opposite. Moreover, the cost-saving effect associated to joint ventures or R&D cartels is confirmed for industries where firms rely mainly upon own R&D as a source of innovation. Finally, in the case of technologically progressive industries cooperating in R&D increases the transmission of knowledge, thereby enhancing spillovers.

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## APPENDIX

*Proof of Remark 1* For generic spillover levels, the relevant FOC for firm  $i$  is:

$$\frac{\partial \pi_i}{\partial x_i} = \frac{2(2 - \beta_i)[a - c + (2 - \beta_i)x_i - (1 - 2\beta_j)x_j]}{9} - \gamma(1 + \beta_i)x_i = 0. \quad (5)$$

Imposing  $\beta_i = \beta_j = \beta$  and solving for symmetric effort levels  $x_i = x_j$  yields:<sup>18</sup>

$$x^N = \frac{2(2 - \beta)(a - c)}{(1 + \beta)(9\gamma + 2\beta - 4)}. \quad (6)$$

<sup>18</sup>For a case where the global maximum may involve asymmetric R&D investments at the first stage, see Salant and Shaffer (1998).

Following Poyago-Theotoky (1999), one may endogenise the size of the spillover, depending upon the organizational design of R&D activity. Under independent ventures ( $IV$ ), setting  $\beta_i = 0$  and imposing the obvious symmetry condition  $x_i = x_j$  yields optimal R&D investment  $x^N(IV) = 4(a - c)/(9\gamma - 4)$ , which is acceptable for all  $\gamma > 4/9$ .<sup>19</sup> Equilibrium outputs are  $q^N(IV) = 3(a - c)\gamma/(9\gamma - 4)$ . The corresponding equilibrium profits, consumer surplus and social welfare are  $\pi^N(IV) = (a - c)^2\gamma(9\gamma - 8)/(9\gamma - 4)^2$ ;  $CS^N(IV) = 18(a - c)^2\gamma^2/(9\gamma - 4)^2$ ; and  $SW^N(IV) = 2\pi^N(IV) + CS^N(IV) = 4(a - c)^2\gamma/(9\gamma - 4)$ .

Under joint venture ( $JV$ ), setting  $\beta_i = 1$  and imposing again symmetry  $x_i = x_j$  yields individual equilibrium R&D effort  $x^N(JV) = (a - c)/(9\gamma - 2)$ , which is acceptable for all  $\gamma > 2/9$ . The equilibrium per-firm production level of the final good is  $q^N(JV) = 3(a - c)\gamma/(9\gamma - 2)$ . The corresponding equilibrium profits, consumer surplus and social welfare are  $\pi^N(JV) = (a - c)^2\gamma(9\gamma - 1)/(9\gamma - 2)^2$ ;  $CS^N(JV) = 18(a - c)^2\gamma^2/(9\gamma - 2)^2$ ; and  $SW^N(JV) = 2\pi^N(JV) + CS^N(JV) = 2(a - c)^2\gamma(18\gamma - 1)/(9\gamma - 2)^2$ .

A straightforward comparison of  $x^N(IV)$  and  $x^N(JV)$  yields the Remark.

*Proof of Lemma 2* The cartel problem, defined for generic spillover levels, is:

$$\max_{x_1, x_2} \Pi^C = \pi_1 + \pi_2 = \frac{1}{9} \sum_{i=1}^2 [a - c + x_i(2 - \beta_i) - x_j(1 - 2\beta_j)]^2 - \frac{\gamma}{2} \sum_{i=1}^2 (1 + \beta_i)x_i^2. \tag{7}$$

Under the reasonable assumption that  $\beta_i = \beta_j = \beta$ , the optimal investment is:

$$x_i = x_j = x^C = \frac{2(a - c)}{9\gamma - 2\beta - 2}. \tag{8}$$

Then, substituting and simplifying yields individual output levels  $q^C = 3(a - c)\gamma/(9\gamma - 2\beta - 2)$  and cartel profits  $\pi^C = (a - c)^2\gamma/(9\gamma - 2\beta - 2)$ . Consumer surplus at the cooperative equilibrium amounts to  $CS^C = 18(a - c)^2\gamma^2/(9\gamma - 2\beta - 2)^2$ , and finally social welfare is  $SW^C = 4(a - c)^2\gamma(9\gamma - \beta - 1)/(9\gamma - 2\beta - 2)^2$ . Setting  $\beta = 0$  or  $\beta = 1$ , alternatively, yields the relevant equilibrium magnitudes in the cases of independent ventures or joint ventures, respectively.

*Proof of Proposition 4* Assume firm 1 plays the leader's role. Again, the three-stage game is solved by backward induction. The leader's problem consists in:

$$\max_{q_1} \pi_1 = (a - q_1 - q_2 - c + x_1 + \beta_2 x_2)q_1 - \frac{\gamma}{2}(1 + \beta_1)x_1^2 \tag{9}$$

under the constraint represented by the follower's reaction function:

$$q_2 = \frac{a - c - q_1 + \beta_1 x_1 + x_2}{2}. \tag{10}$$

<sup>19</sup>Asymptotic stability requires that

$$\left(\frac{\partial^2 \pi_i}{\partial x_i^2}\right) - \left(\frac{\partial^2 \pi_i}{\partial x_i \partial x_j}\right)^2 \geq 0,$$

in an open neighbourhood of the equilibrium. For the sake of brevity, we omit the related calculations. See Qiu (1997).

The leader's optimum at the market stage is then easily calculated:

$$q_1^{SL} = \frac{a - c - \beta_1 x_1 - x_2}{2} + x_1 - \beta_2 x_2. \tag{11}$$

Superscript *SL* stands for *Stackelberg leader*. The resulting profit functions at the second stage are:

$$\pi_1 = \frac{[a - c + (2 - \beta_1)x_1 + (2\beta_2 - 1)x_2]^2}{8} - \frac{\gamma(1 + \beta_1)x_1^2}{2}; \tag{12}$$

$$\pi_2 = \frac{[a - c - (2 - 3\beta_1)x_1 + (3 - 2\beta_2)x_2]^2}{16} - \frac{\gamma(1 + \beta_2)x_2^2}{2}, \tag{13}$$

where superscript *SF* stands for *Stackelberg follower*. Here, the analysis of the first two stages is more involved than under Cournot-Nash behavior, due to the asymmetry associated with the above Stackelberg solution at the market stage.

Suppose first that spillovers  $\beta_i$  are exogenously given. If so, firms proceed to optimize w.r.t. R&D efforts to obtain  $x_1^{SL}(\beta_1, \beta_2)$  and  $x_2^{SF}(\beta_1, \beta_2)$ .<sup>20</sup>

It can be established that  $x_1^{SL}(\beta_1, \beta_2) > x_2^{SF}(\beta_1, \beta_2)$  for all

$$\beta_1 \in \left[ 0, \frac{(2\beta_2 + 1)\beta_2 - 6 - 5\gamma + \sqrt{\Theta}}{2(2\beta_2 - 3)} \right), \tag{14}$$

where

$$\Theta = [5\gamma - \beta_2(2\beta_2 + 1) + 6]^2 - 4(2\beta_2 - 3)[2(2\beta_2 - 3\gamma - 3) - \gamma]. \tag{15}$$

Conversely,  $x_1^{SL}(\beta_1, \beta_2) < x_2^{SF}(\beta_1, \beta_2)$  for all values of  $\beta_1$  higher than the upper bound of the interval specified in (14). Therefore, given generic spillover levels, the comparison between firms' R&D investments yields ambiguous results if Stackelberg competition at the third stage is considered.<sup>21</sup>

However, this ambivalence vanishes if spillovers are endogenous. It can be quickly checked that, under strictly noncooperative behavior, both firms find it profitable to reduce spillovers as much as possible, *i.e.*,  $\partial\pi_i/\partial\beta_i < 0 \forall i$ . As an illustration, suppose firms can perfectly control spillovers. Since  $\partial\pi_i/\partial\beta_i < 0$ , at the second stage both firms set  $\beta_i = 0$ . Hence, the relevant objective functions at the first stage become:

$$\pi_1 = \frac{(a - c + 2x_1 - x_2)^2}{8} - \frac{\gamma x_1^2}{2}; \tag{16}$$

$$\pi_2 = \frac{(a - c - 2x_1 + 3x_2)^2}{16} - \frac{\gamma x_2^2}{2}. \tag{17}$$

The FOCs are:

$$\frac{\partial\pi_1}{\partial x_1} = \frac{a - c + 2(1 - \gamma)x_1 - x_2}{2} = 0 \tag{18}$$

$$\frac{\partial\pi_2}{\partial x_2} = \frac{3(a - c) - 6x_1 + (9 - 8\gamma)x_2}{4} = 0 \tag{19}$$

<sup>20</sup>The expressions for  $x_1^{SL}(\beta_1, \beta_2)$  and  $x_2^{SF}(\beta_1, \beta_2)$  are omitted for brevity. They are available upon request.

<sup>21</sup>This result is broadly in line with previous literature on asymmetric R&D races (see Grossman and Shapiro, 1987; Delbono and Denicolò, 1991, *inter alia*).

yielding

$$x_1^{SL} = \frac{2(a-c)(2\gamma-3)}{8\gamma^2-17\gamma+6}; \quad x_2^{SF} = \frac{3(a-c)(\gamma-2)}{8\gamma^2-17\gamma+6} \quad (20)$$

as the equilibrium R&D investment. Observe that  $x_1$  and  $x_2$  are both positive if  $\gamma > 2$ . Obviously, this constraint comes from the follower's solution.<sup>22</sup> Moreover, notice that  $x_1^{SL} > x_2^{SF}$ . Then, the above discussion, together with the comparison between (20) and (6) suffice to derive Proposition 4.

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<sup>22</sup>Second order conditions are met for all  $\gamma > 9/8$ .