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R&D investments and spillovers under endogenous technological opportunity: Why competing firms invest more as spillovers increase but less than cooperating firms no matter the degree of exogenous spillovers?

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R&D investments and spillovers under endogenous technological opportunity:

Why competing firms invest more as spillovers increase but less than cooperating firms no matter the degree of exogenous spillovers?

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Abstract:
In this paper, we focus on endogenous technological opportunity and its effects upon R&D outcomes in the independent and cooperative cases. In light of the importance of spillovers in economic analysis of R&D incentives, we examine the relationship between R&D appropriability and R&D investment in the presence of an endogenous technological opportunity. In order to do this, we develop a three-stage game in which firms first choose their R&D orientations, then how much to invest in R&D, and finally their Cournot outputs. Contrary to the usual assumption made in oligopoly models that technological opportunity is external to the industry where firms operate, we fully endogenize technological possibilities through the firms' choices of their R&D approaches.
We find that competing firms invest more in R&D as spillovers increase (and R&D appropriability diminishes) but still less than cooperating firms no matter the degree of exogenous spillovers. This is a reversal of well-known results established in the literature on R&D and spillovers.

Keywords: Technological opportunity, R&D spillovers, R&D investment, absorptive capacity.

JEL Classification: O30.

1. Introduction

Appropriability of R&D results has been a lively topic in the literature on cooperative and non-cooperative R&D and a matter of technology and antitrust policy concern. Most of the theoretical literature on R&D investments and spillovers has focused on how appropriability conditions of research results affect private incentives to conduct R&D taking the view that the conditions of appropriability, as captured by the extent of spillovers of technological information, are exogenous and beyond the control of firms. In the case of competitive R&D decisions, it has been shown that the existence of exogenous spillovers say, due to imperfect appropriability of patent rights, reduces the incentive of firms to invest in R&D (Spence, 1984). An increase in the degree of spillovers leads to a reduction in firms' R&D expenditures. Instead firms may decide to cooperate in R&D in order to internalize the externality they impose on each other in the competitive process through the formation of a research joint-venture. The comparison of R&D outcomes between the two modes of organizing R&D depends on the extent of spillovers. Cooperative R&D induces higher R&D incentives and leads to higher technological improvement when spillovers are large, while independent R&D leads to higher technological improvement when spillovers are small (Katz, 1986; D'Aspremont and Jacquemin, 1988).

Some subsequent papers on R&D and spillovers have shown however that increases in the extent of exogenous spillovers may encourage R&D under some conditions. In contrast to previous work, Cohen and Levinthal (1989) develop a model in which R&D is necessary to acquire and assimilate external knowledge. A firm's assimilation of competitor' R&D output is constrained by its absorptive capacity. In the presence of endogenous absorptive capacity, the traditional result on the influence of spillovers on R&D spending may change. The desire to assimilate the knowledge generated by other firms provides a positive incentive to invest in R&D as the degree of spillovers increases. The equilibrium R&D increases with the degree of spillovers if the appropriability disincentive effect to invest in R&D is outweighed by the absorptive incentive effect. In addition, Levin e Reiss (1988) show that diminished appropriability does not necessarily reduce R&D expenditures. Under some conditions, an increase in the extent of process (product) spillovers will lead to an increase in product (process) R&D. The degree of substitution between own and rival R&D may affect private incentives to undertake R&R. When the extent of spillovers is near zero, an increase in the extent of process (product) spillovers may induce sufficient substitution between own and rival R&D so as to increase the intensity of product (process) R&D.

This strand of literature treats industry-wide technological opportunity as an exogenous phenomenon beyond the control of firms (De Bondt, 1996). Technological opportunity within a single industry may be described roughly as how costly it is for a firm to achieve technological improvement within that industry. However, the role of technological opportunity in innovation hasn't been adequately accounted for by the existing theoretical literature on R&D and spillovers because the influence of firms' past decisions with respect to R&D investments and R&D paths in realizing technological possibilities was neglected. There is empirical evidence that shows that the capacity of a firm to exploit technological possibilities has a moderating effect on the relationship between technological opportunity available to an industry and innovative performance of the firm.

The so-called technology-push hypothesis emphasizes the role of underlying scientific knowledge in innovation (Kamien and Schwartz, 1982). The pace of innovative activity of firms will depend on the advances in the scientific base of their industry. According to this hypothesis, a firm's research staff may be regarded as the initiator of innovations. A firm with a large research facility will be favored over a smaller firm because its staff will be able to scan a wider range of the scientific base, and may be better able to exploit the existing scientific base and to add to it. However, the technological possibilities opened up by an important scientific advance may not be grasped by established firms. Many innovations may be products of just the creative drive of individual entrepreneurs. The relative contribution of firms of different sizes to innovation in a particular industry might depend on the age of that industry (Rothwell and Dodgson, 1994). During the early stages of an industry cycle, new, small but fast-growing firms play the key role as innovators and, in the later phases of development, innovation requires large firms. It is Schumpeter (1939) who made the initial major contribution to the discussion of industry dynamics.

Schumpeterian models of innovation can be of two types: entrepreneurial innovation and managed innovation (Freeman et al., 1982). The first model corresponds to a vision of innovation taking place in a context of competitive capitalism characterized by exogenous scientific discoveries and inventions that are not economically determined. In this case, risk-taking entrepreneurs grasp the opportunities offered by new scientific developments to create radical innovation, this way fostering the growth of new industries and the emergence of new major product groups. In the managed innovation model, Schumpeter envisions inventive activities as increasingly under the control of large firms and reinforcing their competitive position. Market requirements become increasingly well-specified, and therefore competing products are little differentiated technically. As the technology and the market matures and average firm size increases, inventive activity becomes increasingly internalized in the form of large in-house R&D laboratories. Thereby, the inventive activity becomes an endogenous part of the process of oligopolistic competition.

Thus, the modeling choice of taking technological opportunity as given is partially justified by the environmental conditions under which firms operate in a given industry, but it is important to realize that firms have some power in deciding what portion of the available technological possibilities they exploit. Taking the view that technological opportunity ought to be treated as endogenous and under the control of firms, we would like to pose the question of whether a firm will have an incentive to adopt a firm-specific R&D path in order to enhance its ability to scan and exploit technological possibilities. Whereas identical R&D approaches cause firms to "step on toes" of others, in the sense that if both firms conduct research they are duplicating each other's results in case of no knowledge sharing, the opposite would hold for firm-specific R&D approaches. Would not cooperating firms do a better job at and benefit more from scanning and exploiting opportunities for new innovations than competitive firms? The next question arises whether the higher degree of appropriability that is implied endogenously by the firms' decisions with respect to R&D approaches will remove support to the traditional claim that higher levels of exogenous spillovers reduce R&D investments under R&D competition.

We intend to explain why firms might select idionsyncratic R&D orientations and in consequence traditional results on the qualitative effects of spillovers on R&D investment and on the comparison of R&D outcomes between cooperative R&D and independent R&D might be changed. In order to do this, we develop a duopoly model of cost-reducing technological improvement that incorporates endogenous technological opportunity. We specify a cost function with a constant unit-cost of production that is a function of both firms' "effective" R&D investment. We propose a representation of a firm's effective R&D investment that requires the firm to choose its R&D approach before engaging in R&D with the purpose of benefiting from opportunities for innovations. We adopt Kamien and Zang's (2000) game-structure and strategic choice variables as this is best suited to compare the various papers in the literature on R&D and spillovers. In their model a firm must invest in its own R&D to absorb any of the R&D output of its competitors. In our model, however, the absorptive capacities of firms are not related to their R&D spending. Consequently, the above-mentioned qualitative change of the traditional claim would not be explained by the introduction of that positive absorption incentive.

Our paper generalizes Levin Ross' (1988) analytical framework by considering that both the technological opportunity and the productivity of knowledge spillovers are endogenously determined through the R&D decisions taken by firms in the past. The notions of technological opportunity and productivity of spillovers are dealt with by Levin e Ross in a study on the economic consequences of R&D spillovers. An important distinction between the extent to which usable knowledge spills over to rival firms and the productivity of that shared knowledge is made by Levin and Ross. The technological opportunities and the productivity of spillovers are represented by different elasticities in their theoretical model with constant elasticity specifications for individual firms' unit variable costs, goods prices, and products qualities. In the empirical work that follows, diferences in R&D spending patterns across industries are accounted for by allowing these elasticities to vary with exogenous measures of technological opportunity and appropriability.

This paper extends Wiethaus' (2015) theoretical model by endogenizing the technological opportunities of firms, in addition to their absorptive capacities. R&D spillovers are endogenized in Wiethaus' model by assuming that the ability of a firm to exploit the pool of external knowledge is a function of the R&D orientations selected by firms in the past. Absorptive capacity of a firm is represented in his model with linear specifications for individual firms' unit production costs by a factor less than one of the potential knowledge flows received from rival firms. We endogenize technological opportunities of firms assuming that R&D orientations also influence the extent to which technological possibilities are realized by firms. Thus, R&D approaches chosen by firms in the past not only influence the assimilation of external R&D investment but also the productivity of own R&D effort.

We would expect from R&D competition that increases in exogenous spillovers encourage R&D, which is contrary to what economists in general have long argued. It is our introduction of endogenous technological opportunity that changes the traditional result on the qualitative effects of spillovers on R&D. Next to the appropriability disincentive effect to invest in R&D, there are incentives to adopt more specific R&D approaches in order to realize technological possibilities and to invest in R&D. Following the model assumptions, this reversed result would happen for virtually the entire range of the spillover parameter.

When firms can cooperate, we would expect that they choose purely, idiosyncratic R&D approaches, which is a different outcome from the competitive case. The more the firms' R&D is diverse the higher the firms' ability to scan and exploit the pool of technological possibilities. Cooperating firms are able to fully internalize the benefits from opportunities for new innovations and therefore maximize the realization of technological possibilities. Consequently, the cooperative amount of R&D would be higher than the analogous amount of R&D for the competitive case no matter the level of exogenous spillover. In contrast to traditional results, also cooperative R&D would lead to higher technological improvement when spillovers are small.

The remaining of the paper is organized as follows. In section 2, the assumptions of the game-theoretical model are set out and the structure of the model is developed. Section 3 presents the equilibrium results at the final stage of the game, while sections 4 and 5 present the equilibrium results under R&D competition and R&D cooperation, respectively. Section 6 makes comparisons between the competitive and cooperative solutions regarding the individual level of R&D investment. Section 7 analyses the slope of the reaction functions in R&D investment space and the stability of the oligopoly equilibrium in R&D. The analysis of the evolution of this investment variable with respect to exogenous spillovers under R&D competition is made in section 8. Finally, section 9 concludes the paper.

2. The basic theoretical model

A simple duopoly model can be set up to highligh the role of endogenous technological opportunity in R&D investments. We propose a three-stage game with the following time line. In the first stage, the two firms choose simultaneously their R&D approaches and in the second stage their levels of R&D investment. We consider two versions of the game regarding the firms' decisions on the two elements of their R&D strategies. That is, both the R&D orientations and the R&D investments levels can be choosen either independently or cooperatively. The output level of each duopolist is chosen non-cooperatively in the third stage of the game.

Firms can improve their market profitability by making R&D investments that reduce the unit costs of production.The effective level of unit-cost reduction of firm i depends not only on its own R&D investment, x_i but also on the other firm's R&D investment, x_j via knowledge spillovers, $i, j = 1, 2$ and $i \neq j$. R&D activities are associated with positive spillovers. A firm's knowledge leaks to its rival at an exogenous rate $0 \leq \beta \leq 1$, but shared knowledge is only partly assimilated and absorbed by the rival firm. The absorptive capacity of a firm is dependent upon firms' choices of R&D approaches, or technological distances $0 \leq \delta_i \leq 1$ and $0 \leq \delta_j \leq 1$ by firms i and j, respectively.

Specifically, the effective level of unit-cost reduction of firm i as assumed in this paper is

$$X_i = \left(k + (1-k)\left(1 - (1-\delta_i)(1-\delta_j)\right)\right)x_i + \beta(1-\delta_i)(1-\delta_j)x_j,\ i = 1,2,\ i \neq j. \quad (1)$$

The marginal productivity of a firm's own R&D investment is implied by the technological opportunity available to an industry and the extent it is realized by the firm. The technological opportunity faced by the firm in engaging in R&D is characterized by an exogenous parameter k and two choice variables, δ_i and δ_j. Parameter k, with $0 \leq k \leq 1$, denotes the extent to which the technological opportunity of the firm is exogenously determined. Exogenous factors such as the degree of usable extra-industry knowledge and the degree to which new extra-industry knowledge improves the innovative performance of the firm shape k. Although not formally captured on our essentially static theoretical framework, we think of k as being cumulatively built through past as well as current R&D investment of government or university laboratories.

The ability of a firm to scan and exploit technological possibilities is determined by the choices of R&D approaches made early on. In this sense the technological opportunity faced by the firm in engaging in R&D becomes endogenous. Equation (1) reflects the assumption that technological possibilities are realized through the interaction of k and δ_i and δ_j. A large k means that the pool of innovation opportunities is plentiful as it is replenished faster than it can be "fished out" by the firms' decisions to carry out R&D, while a low k means that the pool of innovation opportunities becomes meager unless the firms are willing to not adopt similar research paths in order not to make the technology characteristic space more densely packed. This formulation of exploitative capacity of a firm and its economic consequences on cost reduction is based on the brief literature review provided in the introduction of the paper.

The conventional literature assumes that the marginal productivity of own R&D is constant and equal to unity. The technological opportunity faced by a firm is therefore assumed to be environmentally determined, that is, $k = 1$ in our model specification for X_i, (1). In this extreme case, the realization of technological opportunity is independent of firms' choices of technological distances. The 100% potential of technological opportunity is by assumption fully exploited by firms.

In this paper, we analize the opposite case where the technological opportunity of a firm is fully endogeneous, that is, $k = 0$. In this extreme case, the extent to which technological possibilities are realized by firms depends completely on their capacity to scan and exploit the existing knowledge base. Therefore, the full potential of the technological possibilities may turn out to be only partly exploited by the firm as an equilibrium result of their past choices of technological distance. The full potential of technology can only be realized through the choice of purely idiosyncratic, firm-specific R&D orientations by both firms, $\delta = 1$. This behavior underlying the innovation process may mean that firms' search for knowledge span over the widest range of innovative possibilities. The benefits of search knowledge increase with technological distances. The marginal productivity of own R&D, i.e. the marginal impact on cost reduction of x_i, is minimal when both firms choose purely broad, identical R&D approaches $\delta = 0$, meaning that all firms are competing for the same innovative possibilities.

Firms can reduce their constant unit-cost of production *A* by the amount of their effective R&D level X_i.The R&D technology they employ exhibits diminishing returns, as each firm's costs of R&D investment x_i is quadratic, $(\gamma/2)x_i^2$.

Each firm seeks to maximize individual profit

$$\pi_i = \left(a - q_i - q_j\right)q_i - (A - X_i)q_i - \frac{\gamma}{2}x_i^2, \quad i = 1, 2,\ i \neq j. \tag{2}$$

where *a* is the highest consumer reservation price, and q_i and q_j quantities produced by firm i and firm j, respectively. The demand function $P(Q) = a - q_i - q_j$ determines the market price *P* as a linear function of the market quantity $Q = q_i + q_j$.

3. Third stage equilibrium results

The method of backward induction is adopted to find the equilibrium values of the model, and therefore the quantity choices at the final stage of the game are derived first. From the profit function (2), we obtain optimal output quantities as

$$q_i = \frac{1}{3}\left(a - A + 2X_i - X_j\right), \quad i = 1, 2,\ i \neq j\ . \tag{3}$$

4. Equilibrium results in R&D competition

4.1 Caracterization of the optimal level of R&D investment

In this section we concentrate on the competitive solution both at the initial stage of selection of R&D approaches and the second stage of choice of R&D investments, to deduce the symmetric stage Nash equilibria. Given the equilibrium level of output (3) at the third-stage, the ith firm's profit function of the non-cooperative game's second stage can be expressed as

$$\pi_i = q_i^2 - \frac{\gamma}{2}x_i^2, \quad i = 1, 2. \tag{4}$$

The first-order condition for a maximum of π_i with respect to x_i, $i = 1, 2$, for an interior solution can be written as

$$\frac{\partial \pi_i}{\partial x_i} = 2q_i\frac{\partial q_i}{\partial x_i} - \gamma x_i = 0, \quad i = 1, 2. \tag{5}$$

Note that, from (1) and (3),

$$\frac{\partial q_i}{\partial x_i} = \frac{1}{3}\left(2 - (2 + \beta)(1 - \delta_i)\left(1 - \delta_j\right)\right), \tag{6}$$

For an interior solution, we must have $\partial q_i/\partial x_i > 0$. From (5), we deduce the equilibrium level of investment

$$x_i^* = \frac{2(a-A)\left(2-(2+\beta)(1-\delta_i)(1-\delta_j)\right)}{9\gamma-2\left(2-(2+\beta)(1-\delta_i)(1-\delta_j)\right)\left(1+(-1+\beta)(1-\delta_i)(1-\delta_j)\right)}, \quad i = 1, 2,\ i \neq j. \tag{7}$$

The second-order condition with respect to x_i is satisfied for $\gamma > 8/9$, and to see this just consider the most stringent situation, at $\beta = 0$ if $\delta = 1$, for $k = 0$ – as a matter of fact for any $0 \leq k \leq 1$. By $\gamma > 8/9$, the denominator of the symmetric equilibrium R&D investiment in (7) is non-negative.

In order to obtain the equilibrium values of relevant economic variables, we will conduct numerical simulations by setting γ equal to different values, depending on the type of analysis to be performed. The R&D and spillovers model of section 2 is critical in our simulations, and the specific values of γ to be selected are justified in sections 6 and 7 below. We look at representative numerical examples by assuming throughout that $a - A = 10$. The particular choice of the value of $a - A$ does not influence in any fundamental way the equilibrium results of our numerical examples, in the sense that it doesn't affect the optimal choices of R&D approaches, it only changes the magnitudes of R&D investments of firms and thus their effective unit-cost reductions levels.

4.2 Caracterization of the optimal technological distance

The first-order condition with respect to the R&D approach δ_i for an interior solution, $\partial\pi_i/\partial\delta_i = 0$, can be described by a direct effect and a strategic effect as follows:

$$\frac{\partial\pi_i}{\partial\delta_i} = 2q_i\left(\frac{\partial q_i}{\partial\delta_i} + \frac{\partial q_i}{\partial x_j}\frac{dx_j^*}{d\delta_i}\right), \quad i = 1,2,\ i \neq j. \tag{8}$$

Note that the strategic effects $\partial\pi_i/\partial x_i,\ i = 1,2,$ are zero by the second stage first-order conditions (5) and so are omitted here. To evaluate the overall effect of a change of δ_i on profit, all the derivates on the right side of (8) must then be derived. To begin with, the direct effect,

$$\frac{\partial q_i}{\partial\delta_i} = \frac{1}{3}\Big(\big((2x_i^* - x_j^*) - \beta(2x_j^* - x_i^*)\big)(1 - \delta_j)\Big), \quad i = 1,2,\ i \neq j. \tag{9}$$

is non-negative in δ_i if

$$(2 + \beta)x_i^* \geq (1 + 2\beta)x_j^*, \quad i = 1,2,\ i \neq j. \tag{10}$$

The adoption of a more specific R&D approach increases directly the firm's own profit as long as the rival firm's R&D investment, x_j^* is not too high compared to own R&D investment, x_i^* conditional on the value of β. Under such conditions, a given reduction of the firm's unit-cost of production is achieved with less R&D investment because a more specific R&D approach results in higher ability to exploit the technological possibilities available to firms if, of course, their abilities to exploit technological possibilities have not already attained a maximum at $\delta_j = 1$. However, each firm's exploitative ability and absorptive capacity are both determined by δ_i, the former ability is positively influenced by δ_i whereas the latter capacity is negatively influenced by it. The requirement for $\partial q_i/\partial\delta_i \geq 0$ in (10), from (9), can be expressed as $(2x_i^* - x_j^*) - \beta(2x_j^* - x_i^*) \geq 0$. As such, specificity in R&D is desirable from the perspective of the ith firm if and only if the amount of own R&D investment carried out to realize innovative possibilities is sufficiently higher than its rival R&D investment, so that a higher exploitative capability resulting from a more specific R&D approach, and hence increases of the R&D profitability of the firm (in proportion to $2x_i^* - x_j^*$), compensates for a lower absorptive capacity and hence reductions of the R&D profitability (in proportion to $-\beta\left(2x_j^* - x_i^*\right)$). The requirement for $\partial q_i/\partial\delta_i \geq 0$ in (10) will be satisfied for all $0 \leq \beta \leq 1$ if $x_i^* \geq x_j^*$.

In Wiethaus's (2005) analysis of endogenous absorptive capacity, by contrast, the sign of the counterpart effect of an adoption of a broader (more specific) R&D approach on own profit π_i is non-negative (non-positive). Connecteness to external sources of knowledge for the ith firm pays off as long as the amount of knowledge it receives from a rival is sufficiently high, i.e., $2x_j^* \geq x_i^*$.

Next, for the symmetric case, we have the familiar appropriability term

$$\frac{\partial q_i}{\partial x_j} = \frac{1}{3}(-1 + (1+2\beta)(1-\delta)^2). \qquad (11)$$

The familiar requirement for a rival's additional R&D investment to provide a positive externality on a firm's output and therefore profit is that $\beta \geq 0.5$. From (11), the counterpart requirement for $\partial q_i/\partial x_j \geq 0$ in our model is that

$$-1 + (1+2\beta)(1-\delta)^2 \geq 0. \qquad (12)$$

This implies that $\partial q_i/\partial x_j \geq 0$ for $\beta \geq 0.5$ as long as $\delta \leq 0.292893$, but $\partial q_i/\partial x_j \leq 0$ for $\delta \geq 0.42265$, and for all $0 \leq \beta \leq 1$. As such, (12) is a stronger requirement for a firm to realize a positive externality from its rival R&D investment than the familiar one that $\beta \geq 0.5$.

Finally, the effects of a change in δ_i on the rival's optimal R&D investment in the game's second stage, x_j^* are referred by the derivative

$$\frac{dx_j^*}{d\delta_i} = \frac{2(a-A)(2+\beta)(1-\delta_j)\left(9\gamma - 2\left(2-(2+\beta)(1-\delta_i)(1-\delta_j)\right)^2(-1+\beta)/(2+\beta)\right)}{\left(9\gamma - 2\left(2-(2+\beta)(1-\delta_i)(1-\delta_j)\right)\left(1+(-1+\beta)(1-\delta_i)(1-\delta_j)\right)\right)^2}, \quad i = 1,2,\ i \neq j. \qquad (13)$$

The sign of $dx_j^*/d\delta_i$ is determined by the sign of the numerator of the evaluated derivative since the denominator is non-negative by $\gamma > 8/9$. Hence $dx_j^*/d\delta_i$ is non-negative. This means that the adoption of a more specific R&D approach by firm i results in higher realization of technological possibilities and higher appropriability implied endogenously by the firms' decisions and thus increases the profitability of R&D investments from the perspective of the rival firm.

It can then be said that the non-cooperative R&D game yields two symmetric Nash equilibria in the firms' choices of R&D approaches. One equilibrium is for purely idionsyncratic R&D approaches, $\delta_i^* = 1$, $i = 1,2$. We establish the second equilibrium via numerical simulations and the equilibrium results are shown in Tables 1 and 2 in the appendix. The second one is for firm-specific R&D approaches, $\delta_i^* > 0$ for $\beta > 0$, while $\delta_i^* = 0$ only if $\beta = 0$, $i = 1,2$. In equilibrium, firms may choose intermediate levels of technological distance δ at the initial stage of the game if they act independently. The interior solutions for δ depart significantly from the extreme values 0 and 1 in the unit-interval of technological distances for high β's. In particular, the optimal level $\delta^* = 0.42265$ at $\beta = 1$ is close enough to the middle point 0.5. Anyway, R&D appropriability diminishes as β increases despite decreases in the degree of endogenous appropriability $(1 - \delta_1^*)(1 - \delta_2^*)$ as a result of induced increases in δ_i^*, $i = 1, 2$.

Regarding the interior solution of the game, each competing firm i faces a trade-off in its choice of R&D approach δ_i. To see this, we consider again the direct and strategic effects of a change of δ_i on the ith firm's profit. A trade-off between the positive direct effect in (9) and the negative strategic effect, as given by the product of (11) multiplied by (13), can occurs for all $0 \leq \beta < 1$. From Table 1, it can be observed that the appropriability term $\partial q_i / \partial x_j$ is negative in equilibrium for $\beta < 1$. A more specific R&D approach increases the rival's R&D investments, $dx_j^* / d\delta_i > 0$ which, by $\partial q_i / \partial x_j < 0$ in equilibrium, hurt the firm's own profit. Hence, the strategic effect associated with the adoption of a more specific approach hurt firm i. The direct effect is positive for $\beta < 1$.

The direct effect exactly matchs the negative strategic effect at $\beta = 0$ if $\delta = 0$. The direct effect dominates the negative strategic effect for $\beta > 0$, and as a result firms will choose more specific approaches, $\delta > 0$; otherwise, firms would choose purely identical approaches, $\delta = 0$. Whenever the direct effect dominates the strategic effect, firms will react by choosing a slightly more specific R&D approach. Note that, at $\beta = 1$, the direct effect is equal to zero regardless of the choice of δ, while the appropriability term is zero in equilibrium and so is the strategic effect.

The decision whether or not to adopt a slightly more specific R&D approach apparently involved a trade-off between higher exploitation of innovative possibilities and appropriability of own R&D on the one hand, and higher assimilation and absorption of external knowledge on the other hand. From the perspective of firms, similarity and variety of R&D approaches seem to be in conflict with each other. The important challenge for firms' management is therefore to balance between similarity and diversity of R&D approaches. The intermediate levels of δ chosen by firms in non-cooperative equilibrium reveal that firms do strick such a balance between similarity and variety.

Our analysis confirms Kamien and Zang's (2000) prediction that competing firms choose idyosincratic R&D approaches. We establish a second Nash equilibrium in the game's first stage too. Our model shows that competing firms choose intermediate levels of technological distance in order to improve their ability to exploit technological opportunities. Hence, our analysis appears to contradict Wiethaus' finding that competing firms choose fairly broad (identical) R&D approaches. In their models, optimal distances are either fairly close to the extreme $\delta = 0$ in the spectrum of technological distances or coincident with the extreme $\delta = 1$. R&D competition there means either technological similarity or technological variety.

Nooteboom et al. (2007) test the relation between cognitive distance and innovation performance of firms engaged in technology-based alliances. The key finding is that the hypothesis of an inverted U-shaped effect of cognitive distance on innovation performance of firms is confirmed in the case of explorative learning. The optimal cognitive distance at the mean value of technological capital is 38.4 on a scale between zero and hundred. The key contribution that their paper makes is that it shows the opposed effects of small versus large distances in cognition, and the implications of this combined effect for firm performance. The authors have interpreted cognitive distance in terms of differences in technological knowledge between firms.

5. Equilibrium results in R&D cooperation

5.1 Caracterization of the optimal level of R&D investment

In this section, we model R&D cooperation as a research joint venture and look for only a symmetric equilibrium, at the stage of choice of R&D investments as well as at the previous stage of choice of technological distances. If the firms behave cooperatively in choosing their R&D investments, the joint profit function in the game's second stage is

$$\pi_i + \pi_j = q_i^2 + q_j^2 - \frac{\gamma}{2}x_i^2 - \frac{\gamma}{2}x_j^2, \quad i = 1, 2,\ i \neq j. \tag{14}$$

The maximum of $\pi_i + \pi_j$ can be determined by the first- and second-order conditions. From (14) we derive the first-order conditions with respect to x_i, $i = 1, 2$, which can be expressed as

$$\frac{\partial(\pi_i+\pi_j)}{\partial x_i} = 2q_i\frac{\partial q_i}{\partial x_i} + 2q_j\frac{\partial q_j}{\partial x_i} - \gamma x_i = 0, \quad i = 1, 2,\ i \neq j. \tag{15}$$

Thus, in maximizing joint profits, each firm internalizes the externality $2q_j\, \partial q_j/\partial x_i$ it imposes on the other firm. We use these equilibrium conditions to deduce the optimal level of individual investment

$$\hat{x}_i = \frac{2(a-A)\left(1+(-1+\beta)(1-\delta_i)(1-\delta_j)\right)}{9\gamma - 2\left(1+(-1+\beta)(1-\delta_i)(1-\delta_j)\right)^2}, \quad i = 1, 2,\ i \neq j. \tag{16}$$

The second-order conditions for a maximum need to be satisfied too. Parameter γ needs to get large enough in order for these conditions to be satisfied. For $k = 0$ –actually, for any k -, and for all $0 \leq \beta \leq 1$, given that the most stringent case is if technological distance $\delta = 1$, we conclude that the critical value of γ is 10/9.

5.2 Characterization of the optimal technological distance

In R&D cooperation, the maximization of joint profit with respect to R&D approaches requires the satisfaction of the first-order conditions with respect to δ_i, $i = 1, 2$, which are

$$\frac{\partial(\pi_i+\pi_j)}{\partial \delta_i} = 2q_i\frac{\partial q_i}{\partial \delta_i} + 2q_j\frac{\partial q_j}{\partial \delta_i} = 0, \quad i = 1, 2,\ i \neq j. \tag{17}$$

By the second stage first-order conditions (15), the strategic effects are zero, $\partial\pi_i/\partial x_i + \partial\pi_j/\partial x_i = 0$, $i = 1, 2$, $i \neq j$, and so they are omitted here. In maximizing profits, each firm internalizes the positive externality $2q_j\, \partial q_j/\partial\delta_i$ that an increase in its distance δ_i confers on its rivals' output and therefore profit. In the symmetric case $\hat{x}_i = \hat{x}_j$, and $X_i = X_j$ and $2X_i - X_j = 2X_j - X_i$ in equilibrium, and therefore $q_i = q_j$ from (3) and $\partial q_i/\partial\delta_i = \partial q_j/\partial\delta_i$, and so (17) reduces to

$$\frac{\partial(\pi_i+\pi_j)}{\partial\delta_i} = 4q_i\frac{\partial q_i}{\partial\delta_i} = 0, \quad i = 1,2,\ i \neq j. \tag{18}$$

From (9), for the symmetric cooperative case, joint profits are maximized provided that

$$\frac{\partial q_i}{\partial\delta_i} = \frac{1}{3}(1-\beta)(1-\delta)\hat{x}_i = 0, \quad i = 1,2. \tag{19}$$

Note that to evaluate (9) for the cooperative case we substitute for x_i^* from $\hat{x}_i$, and for the non-cooperative solution for technological distance δ from the cooperative solution for δ. We expect cooperating firms to adopt purely idiosyncratic R&D approaches because they can internalise the beneficial effects of technological opportunities. We replaced δ by δ_j in (19) for the sake of the derivation of the symmetric Nash equilibrium next. For $\beta < 1$, we have that $1-\beta > 0$. For $1-\beta > 0$ and therefore $\partial q_i/\partial\delta_i > 0$ for every $\delta_j \neq 1$, the satisfaction of (19) requires $\delta_i = 1$ in a symmetric equilibrium. At $\beta = 1$ and therefore $1-\beta = 0$, the optimal solution could be either $\delta = 0$ or $\delta = 1$, or any value of δ in between. We have studied the behavior of the objective function as δ_i changes when $\delta_j = 1$ in order to make sure that the critical value of δ that satisfies the first-order conditions also maximizes joint profits. By inspection, given the absence of strategic interaction between firms at the game's first stage, it is evident that $\pi_i + \pi_j$ is maximized at $\delta = 1$.

Thus, the cooperative R&D game yields a unique symmetric Nash equilibrium in the firms' choices of R&D approaches for $0 \leq \beta < 1$, and a multiplicity of equilibria $\hat{\delta}_i$ whereby $0 \leq \hat{\delta}_i \leq 1$ at $\beta = 1$, $i = 1,2$. If firms cooperate in R&D, then $\hat{\delta}_i = 1$ is the unique symmetric equilibrium of the game´s first stage for $0 \leq \beta < 1$, while $\hat{\delta}_i = 0$ is an equilibrium only if $\beta = 1$, $i = 1,2$.

We propose to interpret the differences in technological possibilities scanned and exploited by firms in terms of the technological distance between firms. Our result shows the beneficial effects of large distances in technology for a firm's innovation performance or in our terms, of a large degree of technological nonoverlap. Technological distance yields opportunities for new innovations. As technological distance increases, it has a positive effect on innovation. We would, according to existing literature, expect competing firms to adopt purely idiosyncratic R&D approaches because they can secure perfect appropriability of their R&D investments. But we find that also cooperating firms adopt firm-specific R&D approaches. Their purpose is to benefit from search knowledge by maximizing the search span over the innovative possibilities that are available. The R&D approaches selected by firms determine several different research paths to be followed simultaneously by different firms in the R&D process, as firms decide cooperatively not to "step on toes" of others doing similar design and development work. Each firm deals with different, mutually exclusive technological opportunities, this way enabling them to raise collectively the realization of available opportunities in the form of new innovations.

Our analysis shows that when the firms cooperate in R&D, then $\hat{\delta}_i = 1$, $i = 1,2$, is the unique symmetric equilibrium of the game's first stage ($0 \leq \beta < 1$). Hence our results contradict the previous finding by Kamien and Zang (2000) who find that cooperating firms adopt purely broad R&D approaches in order to maximize knowledge flows between each other. It should be noted that R&D cooperation means either extreme similarity or extreme diversity of R&D approaches. Both studies by Kamien and Zang, and Wiethaus (2005) implicitly treat technological distance as only a problem for a firm's innovation performance instead of also an opportunity. In this paper we address the important issue of the beneficial effects of technological distance, and the differential performance effects when technological distances are either very small, or alternatively, very large.

There can be a negative externality in research which is analogous to congestion on a highway. It is possible that, at some point in time, the duplication and overlap of research reduce the marginal product of research in generating innovations. If you double the amount of skilled labor devoted to research, then you will less than double output – that is, the frequency of innovations. The externality associated with duplication is referred to as the "stepping on toes" effect in Jones (1998). In a R&D process involving many possible research paths and trial and error, it is reasonable for each firm to pursue several research avenues simultaneously, the differences among the firms being in the greater emphasis each places on one over the others (Kamien et al., 1992). The spillover effects in this vision of the R&D process take the form of each firm learning something about the others' experiences. The information acquired in this way on which approaches appear more promising and which ones are less promissing enables a firm to improve the efficiency of its R&D process by concentrating on the more promising approaches and avoiding the others. Under R&D cooperation, firms will always choose to completely share their information. As a result, the cost of duplicating fruitful and fruitless approaches is avoided.

Acccording to Nelson (1961), parallel development of alternative designs seems called for when several competing designs have been proposed and there is considerable uncertainty with respect to which is best, and when much additional information can be gained from prototype testing. The parallel-path strategy implies that no line of general background scientific research appears particularly promising as a source of the information required to permit better development choices than the parallel running of several alternatives. In the parallel-path strategy, information about a development alternative is acquired by doing the same things that would be done were the alternative actually chosen. The information acquired in doing early development work on an alternative design is likely to relate almost exclusively to that design. If the early stage development costs are small, it may be economical not to choose one design or contractor for an R&D job on the basis of first estimates, but rather to run multiple projects, cutting down the list of competing projects as estimates improve.

6. Comparison between competitive and cooperative solutions for R&D investments

In this section we compare the individual level of R&D investment in the case where the two firms compete in R&D with the corresponding individual level in the case where the dupolists cooperate in R&D. The purpose of the following analysis is to determine whether or not the cooperative equilibrium entails a higher level of individual R&D investment relative to the non-cooperative case for all $0 \leq \beta \leq 1$. Is is possible to state $\hat{x} \geq x^{*}$ as an inequality unconditional on the exogenous rate of spillovers, β? If so, this result will differ from any other known in the conventional literature implicitly assuming that $k = 1$. The results concerning the relative magnitude of x^* and $\hat{x}$ in the existing literature therefore could not be generalized to $k = 0$.

We look at a representative example for obtaining equilibrium results. We need to set the proper restriction on the value of parameter γ according to the relevant equilibrium existence requirements before we can compare the cooperative and independent cases in a quantitative manner. The numerical simulations conducted for the purpose of comparing x^* with $\hat{x}$ must assume that $\gamma > 8/9$, which is the critical value of γ derived from the second-order conditions with respect to x_i in R&D cooperation. In the analysis that follows, we set $\gamma = 11/9$, which satisfies the second-order conditions in cooperation and therefore the analogous requirement for a maximum of profit with respect to x_i in R&D competition.

We can use Table 1 containing our findings of the numerical simulations to compare the cooperative and competitive cases. From Table 1 it is obvious that as far as R&D investment per firm is concerned $\hat{x} \geq x^*$, i.e., cooperation in R&D results in the highest R&D investment for $\beta < 1$, while $\hat{x}$ is identical to x^* at $\beta = 1$. To explain this result, we need to compare the marginal incentives to undertake R&D in cooperation with the marginal incentives to undertake R&D in competition, both shown in Table 1. The values of these marginal incentives are functions of the optimal technological distances in cooperation and competition (see subsections 4.2 and 5.2 above).

The equilibrium level of R&D investment in competition in (7) can be expressed as a function of the incentives at the margin to perform R&D in competition $\partial q_i/\partial x_i$ and $\partial q_i/\partial x_j$ from (6) and (11), respectively, and a parameter γ. Note that, in the symmetric case, $\partial q_i/\partial x_j = \partial q_j/\partial x_i$. From (6) and (11), we have for the symmetric case that

$$\frac{\partial q_i}{\partial x_i} + \frac{\partial q_i}{\partial x_j} = \frac{1}{3}(1 + (-1 + \beta)(1 - \delta)^2), \quad i = 1, 2,\ i \neq j. \tag{20}$$

Thus,

$$x_i^* = \frac{2(a-A)\partial q_i/\partial x_i}{3\gamma - 6\partial q_i/\partial x_i(\partial q_i/\partial x_i + \partial q_i/\partial x_j)}, \quad i = 1, 2,\ i \neq j. \tag{21}$$

We can also re-express the equilibrium level of R&D investment in cooperation in (16) using the sum of incentives at the margin $\partial q_i/\partial x_i$ and $\partial q_j/\partial x_i$ as included in the first-order conditions with respect to x_i, (15). Note that, in the symmetric case $q_i = q_j$ from (3) and the sum $\partial q_i/\partial x_j + \partial q_j/\partial x_i$ is to be evaluated at the cooperative solution for technological distance δ. Thus,

$$\hat{x}_i = \frac{2(a-A)(\partial q_i/\partial x_i + \partial q_j/\partial x_i)}{3\gamma - 6(\partial q_i/\partial x_i + \partial q_j/\partial x_i)^2}, \quad i = 1, 2,\ i \neq j. \tag{22}$$

While the incentives at the margin in R&D competition depend indirectly on γ via the previous optimal choice of δ, the incentives at the margin in cooperation do not. The optimal distance in R&D cooperation is the same regardless of the particular value of γ selected in the simulations.

It has been shown by the existing literature on R&D spillovers (d'Aspremont and Jacquemin, 1988) that the sign of the so-called appropriabiliy term $\partial q_j/\partial x_i$, which depends on the extent of technological spillovers capturing the exogenous conditions of appropriability of R&D results, determines by itself the relative magnitudes of individual R&D investments in cooperative R&D and independent R&D. This externality term is well-known from the research joint venture literature. Firms can internalize this externality through cooperative arrangements like research joint ventures. If $\partial q_j/\partial x_i > 0$, then when the firms cooperate in their R&D investments they increase it so as to increase the positive externality on each other. Each firm participating in such a cooperative agreement has an incentive to increase R&D investments when it rival does so. As a result, both firms end up with higher cost reductions due to higher R&D investments.

It can be shown in our model, however, that the sign of the difference between the cooperative R&D investment level and the non-cooperative investment level, $\hat{x} - x^*$ is different from the sign of $\partial q_i/\partial x_j$. There is no difference as far as the signs of $\partial q_i/\partial x_j$ predicted under the two types of strategic behavior are concerned, although their respective optimal choices of δ are different. Thus, the cooperative R&D investment level $\hat{x}$ exceeds the non-cooperative R&D investment level x^* precisely when the externality term $\partial q_i/\partial x_j < 0$. Moreover, it is no longer adequate to designate $\partial q_i/\partial x_j$ as the apropriability term in R&D cooperation, because the sign of this derivative does not depend on the value of β, nor does it change the relative magnitudes of $\hat{x}$ and x^*. Neither a lower exogenous apropriability, ie., a larger β ever alters the sign of this partial derivative from negative to positive in equilibrium, nor does the fact that this derivative remains negative ever prevents $\hat{x} \geq x^*$ for all β. In the case of fully endogenous technological opportunity, i.e., $k = 0$, the parameter of institutional apropriability, β is removed of any capacity, by itself or in conjunction with the induced choices of δ to influence the relative magnitudes of $\hat{x}$ and x^*. As such, it is the introduction of a large k and, particularly, the oppositive case of exogenous technological opportunity, ie., $k = 1$, that actually creates the possibility that equilibrium results $\hat{x}$ and x^* be influenced in such a distinctive manner by the exogenous parameter β.

We can show that the individual levels of R&D investment in the competitive and cooperative cases do not depend on the externality term $\partial q_j/\partial x_i$ only, but also on $\partial q_i/\partial x_i$, and that both these marginal incentives to invest in R&D can be very different in competiton and cooperation due to the optimal choices of δ in one and other type of strategic behavior. Thus, notwithstanding $\partial q_j/\partial x_i < 0$ in cooperation, because $\partial q_i/\partial x_i$ in cooperation can exceed considerably $\partial q_i/\partial x_i$ in competition, it is possible that $\hat{x} \geq x^*$ for all β.

For $k = 0$, $\delta = 1$ is the optimal distance in R&D cooperation, while the optimal distances in competition are close to zero for low β's and never exceeding 0.5 for high β's, but still $\partial q_j/\partial x_i < 0$ in both cooperative and competitive cases. In spite of $\partial q_j/\partial x_i\,|_{coop.} < \partial q_j/\partial x_i\,|_{comp.} < 0$ for $\beta < 1$, $\partial q_i/\partial x_i$ in cooperation is enough higher than $\partial q_i/\partial x_i$ in competition that $\partial q_i/\partial x_i + \partial q_j/\partial x_i\,|_{coop.} > \partial q_i/\partial x_i + \partial q_j/\partial x_i\,|_{comp.}$. As a result, from (21) and (22), we have that $\hat{x} - x^* > 0$. At $\beta = 1$, $\partial q_j/\partial x_i\,|_{comp.} = 0$ and $\hat{x} = x^* = 2.2(2)$. Looking at the incentives at the margin to undertake R&D in (21) and (22), a sufficient condition for $\hat{x} = x^*$ is that $\partial q_i/\partial x_i + \partial q_j/\partial x_i\,|_{coop.} = \partial q_i/\partial x_i\,|_{comp.}$ and $\partial q_j/\partial x_i\,|_{comp.} = 0$.

Our model shows that the equilibrium non-cooperative R&D investment level, x^* will not exceed the cooperative R&D investment level, $\hat{x}$ at any β. The relative magnitudes of individual R&D investments under the two forms of strategic behavior do not depend on β. Therefore, our result seems to contradict the previous finding by d'Aspremont and Jacquemin that for large spillovers, i.e., $\beta > 0.5$, the level of R&D increases when firms cooperate in R&D, i.e., $\hat{x} > x^*$, whereas for $\beta < 0.5$ we have that $\hat{x} < x^*$. We would expect this finding from the early literature on exogenous R&D spillovers to be confirmed by the model of endogenous absorptive capacity presented by Wiethaus (2005). Wiethaus' model shows that, under R&D competition, for $\beta > 0.884251$ the optimal distance is $\delta > 0$ and the resulting coefficient of x_j in X_i is a constant, $\beta(1-\delta)^2 = 0.884251$, while for $\beta < 0.884251$, the optimal distance is $\delta = 0$. Under R&D cooperation, Wiethaus would expect cooperating firms to select $\delta = 0$ as the optimal distance for all β, which is also the result established by the model of endogenous absorptive capacity by Kamien and Zang (2000). For $\beta > 0.884251$, in the case of R&D competition, the rate of endogenous spillover is $0.5 < \beta(1-\delta)^2 < \beta$. Thus, for $\beta > 0.5$, $\partial q_j/\partial x_i\,|_{coop.} > \partial q_j/\partial x_i\,|_{comp.} > 0$, while for $\beta < 0.5$, we have the same value $\partial q_j/\partial x_i < 0$ in both cases of R&D cooperation and R&D competition. Again, we have that $\hat{x} > x^*$ for $\beta > 0.5$, while $\hat{x} < x^*$ for $\beta < 0.5$.

Our result is similar to Poyago-Theotoky's (1999) result regarding the comparison between $\hat{x}$ and x^*. In the Poyago-Theotoky's model, each duopolist firm chooses how much information to share with its rival rival, i.e., β_i, $i = 1, 2$ is one more choice variable for a firm. Under cooperative R&D, firms will always choose the fully share their information, i.e., $\beta_i = 1$, $i = 1, 2$, while under independent R&D, firms face no incentive to disclose any of their information, and so their profit maximizing choice is $\beta_i = 0$. It is predicted that $\hat{x} > x^*$. However, where we differ is in that we endogeneize spillovers through the firms' choices of R&D approaches and that in equilibrium, coopering firms decide not to disclose their research results by selecting $\delta = 1$. Note that all the four previous models just reviewed implicitly assume in common that $k = 1$.

7. Analysis of the reaction functions in R&D investment space

There are two additional findings of the standard literature that cannot be confirmed by a model of endogenous technological opportunity and absorptive capacity such as ours. The first result is that, in R&D competition, R&D investments are classified as either strategic substitutes or strategic complements depending on whether the extent of exogenous spillovers is regarded as low or high, respectively. It is shown that in the non-cooperative case, firms tend to free-ride on the rivals' knowledge as the level of spillovers increases. Then it is expected that the introduction of large spillovers changes the relative magnitudes of individual R&D investments in the cooperative and independent cases so that $\hat{x} \geq x^*$. Moreover, there is a problem of stability of the oligopoly equilibrium analysed by the conventional literature assuming exogenous technological opportunity and R&D spillovers. Stability is a relevant propriety which is sometimes required of Nash equilibria in oligopoly models. In a model of non-cooperative duopoly first employed by D'Aspremont and Jacquemin (1988), it has shown that stability of the equilibrium in R&D is not assured for very small spillover values. That is, the reaction functions do not cross "correctly" in R&D investment space for small spillovers.

First, we show that, under R&D competition, the firms' reaction functions in R&D investment space are negatively sloped for all $0 \leq \beta < 1$, and so, according to Bulow et al.'s (1985) definition, R&D investment is a strategic substitute. For large spillovers, the endogenous choice of technological distance δ in our model turns R&D into a strategic substitute.

It follows by familiar differentitation methods using the first-order condition with respect to x_i in (5) that the slope of the ith firm's reaction function in R&D investment space can be expressed as

$$\frac{\partial x_i^*}{\partial x_j} = -\frac{\partial^2 \pi_i / \partial x_i \partial x_j}{\partial^2 \pi_i / \partial x_i^2}, \quad i = 1, 2, \ i \neq j. \tag{23}$$

The sign of the slope of the reaction function is given by the sign of $\partial^2 \pi_i / \partial x_i \partial x_j$, as the sign of the denominator of (23) is negative when the second-order condition with respect to x_i is satisfied.

From (1), (3), and the quadratic profit function in individual output quantity in (4), the slope of the ith firm's reaction function can be re-expressed as

$$\frac{\partial x_i^*}{\partial x_j} = -\frac{2(\partial q_i / \partial x_i)(\partial q_i / \partial x_j)}{2(\partial q_i / \partial x_i)^2 - \gamma}, \quad i = 1, 2, \ i \neq j. \tag{24}$$

The sign of the slope of the reaction function, $\partial x_i^* / \partial x_j$ is given by the sign of $\partial q_i / \partial x_j$ in (11). As the denominator of this expression is assumed to be strictly negative in equilibrium, while in the numerator $\partial q_i / \partial x_i > 0$ by (6), the sign of the derivative (24) is identical to the sign of $\partial q_i / \partial x_j$.

We proceed by conducting numerical simulations to obtain equilibrium results. In the computations we have set $\gamma = 8/9$, which suffices to assure the satisfaction of the second-order conditions with respect to x_i, since the most stringent situation, at $\beta = 0$ if $\delta = 1$, never occurs in non-cooperative equilibrium. At $\beta = 0$, the optimal distance is clearly smaller than one, whereas the largest distance in equilibrium is chosen at $\beta = 1$.

We provide in Table 2 the simulation results of the model on the slope of the reaction function. The slope of the reaction functions in R&D space do not change with the degree of exogenous spillovers β, rather it remains negative for $\beta < 1$. Our model predicts that the sign of $\partial q_i / \partial x_j$ is negative under R&D competition for $\beta < 1$. Increases in β alone make it more likely that the sign of $\partial q_i / \partial x_j$ in (11) becomes positive, but increases in optimal distance induced by β completely offset this direct effect. At $\beta = 1$, we have that $\partial x_i^* / \partial x_j = 0$.

Given the endogenous choice of distance δ, under large spillovers, R&D investment levels x_1 and x_2 are negatively related rather than being positively related. What the endogenous choice of δ does is to turn R&D investment into a strategic substitute under large spillovers. Under such circumstances, competing firms tend to free-ride on the other firm's knowledge. Each firm has an incentive to decrease R&D when its rival increases R&D. As a result, both firms will end up with lower unit-cost reduction which leads to a lower technological improvement at the industry level. This result on the strategic nature of R&D investments seems to be related to the conclusion in section 6 below on the relative magnitudes of individual investments in the cooperation and competition cases. We could argue that the reduced level of R&D activity in the noncooperative case relative to the cooperative case is due to the fact that x_1 and x_2 are strategic substitutes for all $\beta < 1$.

Our model shows that, under R&D competition, R&D investment is a strategic substitute as the reaction functions in R&D investment space are sloping downwards for $\beta < 1$. Hence, our result contrasts with the previous finding by Henriques (1990) who, following D'Aspremont and Jacquemin, find that under large spillovers the slopes the reaction functions change. That is, firms' R&D levels are negatively related under small spillovers, while they become positively related under large spillovers.

The stability property in oligopoly games is related to the slope of the reaction functions. We show that, under R&D competition, the reaction functions cross "correctly" in the R&D investment space, i.e., $\left|\partial x_i^*/\partial x_j\right| < 1$ for all $0 \leq \beta \leq 1$. For very small β's, our model of endogenous technological opportunity does not show instability in the R&D investment stage. As such, the introduction of large spillovers is not required to promote stability in the non-cooperative case.

The equilibrium results of the numerical simulations on the satisfaction of the stability requeriment can be consulted in Table 2. When $\gamma = 8/9$, stability is satisfied too. By setting the same value of parameter γ we did to satisfy the equilibrium existence requirement, the requirement that $\left|\partial x_i^*/\partial x_j\right| < 1$ is also met.

Our analysis shows that stability of the equilibrium in the R&D investment stage is assured in the model of endogenous technological opportunity, i.e., $k = 0$. Our result seems to contradict the previous finding by Henriques who shows that the non-cooperative solution as defined by D'Aspremont and Jacquemin is unstable when spillovers are too small. The symmetric duopoly model employed by D'Aspremont and Jacquemin and Henriques implicitly assume that $k = 1$. A larger k turns the variations of x_i more sensitive to variations of x_j, and eventually the absolute magnitude $\left|\partial x_i^*/\partial x_j\right|$ becomes greater than unity for very small β's.

8. Analysis of the evolution of individual investment in R&D competition

Simulation results in section 6 reveal that R&D investment per firm increases in the value of the spillover parameter in the non-cooperative case. In this section, we focus on the relationship between the individual level of R&D investment and exogenous spillovers under R&D competition. We intend to explain why, in a model of endogenous technological opportunity, R&D investment increases in exogenous spillovers for virtually all the values of the spillover parameter. This is a qualitatively different result from the traditional claim that higher levels of spillovers reduce R&D investments. The conventional literature on R&D and exogenous spillovers (Spence, 1984) predicts that free-riding effects arise in market competition from the introduction of large spillovers. It was shown there that, in the non-cooperative case, firms tend to reduce their own R&D investments and free-ride on the other firms' knowledge as the spillover parameter increases.

We look at a numerical example to obtain equilibrium results in the non-cooperative case. In the computations that follow, we set again $\gamma = 8/9$, which is also the choice made in Wiethaus's (2005) model of endogenous absorptive capacity to determine the critical β above which optimal technological distances corresponding to larger β's are interior solutions, and below which optimal distances for smaller β's are corner solutions.

In our model, the equilibrium technological distances are interior solutions, $\delta_i^* > 0$ for all $\beta > 0$, $i = 1, 2$. We find also an equilibrium solution $\delta_i^* = 0$ (limit case) at $\beta = 0$ by setting $\partial\pi_i/\partial\delta_i = 0$ using (8). We can see the simulation results of our example by consulting Table 2. There is no corner solution, $\delta_i^* = 0$ at any β. If that was the case, the parameter of institutional appropriability β would not be able to influence x_i^* through the optimal choice of δ_i, $i = 1, 2$. In that case, the partial derivative $\partial x_i^*/\partial\beta$ would be obtained by differentiation of (7) with respect to β. Then, we would have $\partial x_i^*/\partial\beta < 0$ at $\delta_i = 0$.

We show that, under endogenous technological opportunity, the individual level of R&D investment is strictly increasing in the spillover parameter β, for all $0 < \beta \leq 1$. Optimal distances increase with increases in the exogenous parameter β. Given the endogenous choice of technological distance, differently from the standard proposition on the negative effect of spillovers on R&D investments, the sign of the derivative of x_i^*, $i = 1, 2$, with respect to β is now unambiguously positive.

In order to explore the overall effect of a change of β on x_i^*, it helps to break up the total effect into a direct effect and an indirect effect. The direct effect of an increase in β on x_i^* is due to the smaller institutional appropriability in the industry, while the indirect effect accounts for the impact of induced increases of optimal distances δ_1^* and δ_2^*. Taking the total differential of x_i^* in (7) with respect to β, we have the partial total derivative

$$\frac{\S x_i^*}{\S\beta} = \frac{\partial x_i^*}{\partial\beta} + \sum_{l=1}^{2} \frac{\partial x_i^*}{\partial\delta_l}\frac{d\delta_l^*}{d\beta}, \quad i = 1, 2. \tag{25}$$

The direct effect can be represented by the partial derivative $\partial x_i^*/\partial\beta$ on the right side of (25), whereas the indirect effect can only be expressed by (the sum of) a product of two derivatives, $\partial x_i^*/\partial\delta_l$ and $d\delta_l^*/d\beta$, $l = 1, 2$. Adding the two effects gives the desired partial total derivate of x_i^* with respect to β. The former effect is negative as shown in the standard literature (Spence, 1984), whereas the latter is positive at equilibrium choices $\delta_i^* > 0$, $i = 1, 2$. From (7), we get partial derivatives $\partial x_i^*/\partial\beta$ and $\partial x_i^*/\partial\delta_l$.

In our model, the first stage first-order conditions cannot be solved explicitly. In order to derive $d\delta_i^*/d\beta$, we thus totally differentiate both firm i's first-stage first-order condition $\partial\pi_i/\partial\delta_i = 0$ and the analogous first-order condition for firm j, $\partial\pi_j/\partial\delta_j = 0$ with respect to β. This yields two equations which can be solved for

$$\frac{d\delta_i^*}{d\beta} = \frac{(\partial^2\pi_i/\partial\delta_i\partial\delta_j)(\partial^2\pi_j/\partial\delta_j\partial\beta) - (\partial^2\pi_i/\partial\delta_i\partial\beta)(\partial^2\pi_j/\partial\delta_j^2)}{(\partial^2\pi_i/\partial\delta_i^2)(\partial^2\pi_j/\partial\delta_j^2) - (\partial^2\pi_i/\partial\delta_i\partial\delta_j)(\partial^2\pi_j/\partial\delta_j\partial\delta_i)}, \quad i = 1, 2, \ i \neq j. \tag{26}$$

Now the derivatives of (26) and then (25) can be computed. The evolution of x_i^*, $i = 1, 2$, with respect to β is given by the partial total derivative $\S x_i^*/\S\beta$, as shown in Table 2. We observe an unexpected result for all $0 < \beta \leq 1$, which is $\S x_i^*/\S\beta > 0$. It is the endogenous choice of technological distance that makes possible the change of the sign of $\S x_i^*/\S\beta$. The indirect effect outweights the negative direct effect due to the sufficiently high increases of distance in response to higher β's.

Under endogenous technological opportunity and absorptive capacity, the results change qualitatively as compared to the standard proposition on the effects of spillovers on R&D investments. In addition to an appropriability incentive and an absorption incentive, we now observe a positive incentive to increase equilibrium technological distances associated with technological opportunity and its exploitation. The opportunity incentive effect dominates both the appropriability and absorption effects, and so the equilibrium R&D investment increases with β.

Our analysis shows that R&D investments are strictly increasing in the spillover parameter. Our analysis contradicts Spence's finding that, in the absence of endogenous absorptive capacity and technological opportunity, the sign of the derivative of x_i^*, $i = 1, 2$, with respect to β is unambiguously negative. Our analysis would also contradicts an inference we could draw from Wiethaus' model on endogenous spillovers, i.e., x_i^* does not increase with increases in β. Given the endogenous choice of technological distance δ_i, $i = 1, 2$, we expected that x_i^* would not change with changes in β, for $\beta > 0.884251$. When the extent of knowledge that outflows to a rival firm j is sufficiently high, a still higher spillover rate provides firm i with a positive incentive to increase optimal distance δ_i^*. Differently from the standard proposition that increasing spillovers reduce the incentives to invest in R&D, we would have that $\S x_i^*/\S\beta = 0$. This result is due to two exactly offsetting effects, which are the benefits to the firm of decreasing its rival's absorptive capacity and the loss associated with the diminished appropriability of rents as spillovers increase. The direct effect of lower institutional apropriabilidade, i.e., higher β, is exactly offset by the indirect effect of lower absorptive capacity, i.e., higher induced distance δ_i^*. In the model of endogenous absorpção capacity, notwithstanding the endogenous choice of distance, we have $\S x_i^*/\S\beta = 0$ at most. The two last results on the relationship between x_i^* and β are the consequence of an assumption repeatedly made in the theoretical literature. In fact, both the two previous models assume that technological opportunity is exogenously given.

9. Conclusion

In this paper, we have focused on endogenous technological opportunity and its effects upon R&D outcomes in the independent and cooperative cases. In light of the importance of spillovers in economic analysis of R&D incentives, we have examined the relationship between R&D appropriability and R&D investment in the presence of an endogenous technological opportunity. In order to do this, we have developed a three-stage game in which firms first choose their R&D orientations, then how much to invest in R&D, and finally their Cournot outputs. Contrary to the usual assumption made in oligopoly models that technological opportunity is external to the industry where firms operate, we have fully endogenized technological possibilities through the firms' choices of their R&D approaches.

We found that competing firms invest more in R&D as spillovers increase (and R&D appropriability diminishes) but still less than cooperating firms no matter the degree of exogenous spillovers. This is a reversal of well-known results established in the literature on R&D and spillovers. It is important to realize that it is a firm's ability to influence industry-wide technological opportunity that changes the qualitative effects of this traditionally considered determinant of innovative activity.

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Appendix

β	R&D comp.					R&D coop.				
	δ_i^*	x_i^*	$\partial q_i/\partial x_i$	$\partial q_i/\partial x_j$	$\partial q_i/\partial x_i$ $+\partial q_i/\partial x_j$	$\delta^{\wedge}_i$	$x^{\wedge}_i$	$\partial q_i/\partial x_i$	$\partial q_j/\partial x_i$	$\partial q_i/\partial x_i$ $+\partial q_j/\partial x_i$
0	0	0	0	0	0	1	2.22222	0.666667	-0.333333	0.333333
0.1	0.231664	1.4781	0.253429	-0.0971972	0.1562318	1	2.22222	0.666667	-0.333333	0.333333
0.2	0.277232	1.69984	0.283578	-0.0895497	0.1940283	1	2.22222	0.666667	-0.333333	0.333333
0.3	0.307713	1.83074	0.299233	-0.0777273	0.2215057	1	2.22222	0.666667	-0.333333	0.333333
0.4	0.331504	1.92373	0.309157	-0.0652012	0.2439558	1	2.22222	0.666667	-0.333333	0.333333
0.5	0.351406	1.99597	0.316105	-0.0528839	0.2632211	1	2.22222	0.666667	-0.333333	0.333333
0.6	0.368708	2.05514	0.321274	-0.0410783	0.2801957	1	2.22222	0.666667	-0.333333	0.333333
0.7	0.384118	2.10533	0.325287	-0.0298848	0.2954022	1	2.22222	0.666667	-0.333333	0.333333
0.8	0.398068	2.14897	0.328499	-0.0193208	0.3091782	1	2.22222	0.666667	-0.333333	0.333333
0.9	0.410845	2.18758	0.331133	-0.00936996	0.321763	1	2.22222	0.666667	-0.333333	0.333333
1	0.42265	2.22222	0.333333*	0**	0.333333***	1	2.22222	0.666667	-0.333333	0.333333

TABLE 1: Equilibrium results of technological distance and individual investment under R&D competition and R&D cooperation for g=11/9.
NOTE: Simulations results are actually: *) 0.333334, **) -3.10833 10^{-7}, and ***) 0.333334.

β	δ_i^*	x_i^*	Slope of the reaction function			Effects on the individual investment			
			$\partial x_i^*/\partial x_j$	$\partial q_i/\partial x_i$	$\partial q_i/\partial x_j$	$\S x_i^*/\S\beta$	$\partial x_i^*/\partial\beta$	$\partial x_i^*/\partial\delta_i^*$	$\partial\delta_i^*/\partial\beta$
0	0	0	0	0	0	Indeterminate	-2.5	5	Indeterminate
0.1	0.219289	1.95929	-0.0555475	0.24001	-0.0895295	4.82323	-1.57127	5.1256	0.623781
0.2	0.266928	2.31401	-0.0607896	0.272577	-0.0825492	2.71201	-1.43357	5.47985	0.378257
0.3	0.29949	2.54192	-0.05777	0.290452	-0.0716191	1.94222	-1.35333	5.80128	0.284037
0.4	0.325091	2.71411	-0.0513922	0.302265	-0.060032	1.53775	-1.29672	6.10267	0.232231
0.5	0.34653	2.85443	-0.0434727	0.310814	-0.0486513	1.28579	-1.25276	6.39003	0.198634
0.6	0.365134	2.97385	-0.0348619	0.317352	-0.0377598	1.1122	-1.21657	6.66666	0.174658
0.7	0.381651	3.07837	-0.0260087	0.322547	-0.0274489	0.984263	-1.18556	6.93461	0.156449
0.8	0.396549	3.17167	-0.0171635	0.32679	-0.017734	0.885331	-1.15822	7.19522	0.142007
0.9	0.41014	3.25609	-0.0084661	0.33033	-0.00859417	0.806057	-1.13361	7.44945	0.130189
1	0.42265	3.33334	0*	0.333333**	0***	0.740738	-1.11111	7.698	0.120281

TABLE 2: Equilibrium results, slope of the reaction function and effects on the individual investment under R&D competition for g=8/9.

NOTE: Simulations results are actually: *) $-3.10834\ 10^{-7}$, **) 0.333334, and ***) $-3.10833\ 10^{-7}$.

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