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The Evolution of Cooperation in Patent Races: Theory and Experimental Evidence

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In a dynamic patent race model we analyze the formation and breakup of joint ventures in relation to: (a) the relative as well as absolute position of the firms in the race; (b) the degree of competition in the ex post market. Fudenberg et al. (1983) studied the main features of a patent race when firms compete in R&D, showing that firms in the same position compete fiercely, dissipating the rent from innovation. By contrast, we show that if firms can cooperate or compete in R&D, and if they start in the same position, they cooperate at the outset but break their agreement in the last stage if they will be serious competitors in the downstream market, while, if they can collude in the ex post market, they cooperate from the outset and they innovate jointly. When the firms are lagged by one step, cooperation does not take place, except in the case the value of the race is negative and the cost saving due to cooperation is large. However, cooperation never occurs if the leader is more than one step ahead. Finally, when the firms cooperate in R&D they proceed to the discovery at low speed. We test these conclusions via experiments on the incentive to cooperate during the course of a race. The results of a sample of 86 races support our theoretical conclusions, although the experimental findings are less clear-cut than the theoretical ones.

Keywords: patent race, research joint venture, product market collusion, experimental economics.

JEL Classification: O30, D43, L13.

1 Introduction

The process that leads to an innovation often has the nature of a race: if the innovation is protected by an efficient patent system, only the first firm to complete the development stage gets the patent; the loser gets nothing. In the real world, however, firms have a set of options other than just entering the race or not, ranging from fierce competition to full cooperation, both in the R&D and in the product market.

Moreover, cooperation / competition takes place in a dynamic context, in which cooperation and competition may alternate as conditions in the discovery process change.

Vonortas (1997) and Hagedoorn et al. (2000) have found that the formation and breakup of joint ventures was a major aspect of the evolution of R&D cooperation in the United States in the period 1985–98, with a significant increase in formation of research partnerships in 1985–95, followed by decreases thereafter. Although there are no clear explanations, Brod and Link (1996) pointed out that one reason is due to the changing attention of the Department of Justice toward antitrust violations. In addition, Veugelers and Kesteloot (1997) provided empirical evidence that R&D alliances can be formed between firms (of the same or of different size).

These results call for a theoretical explanation of the circumstances in which a stable cooperative agreement takes place in the discovery process, and of the conditions that lead firms to break up the venture.

This paper studies the evolution of cooperation in a dynamic patent race à la Fudenberg et al. (1983). While models of patent races are numerous indeed, not many consider the dynamic interaction between firms in the course of the race.[1] The framework of Fudenberg et al. (1983) has several features making for a more realistic description than other dynamic models of R&D.

First, they consider the learning process and knowledge accumulation during the discovery process.[2] Second, they make the more realistic assumption that firms may revise their decisions during the course of the race, depending on how they stand, which enables one to study the patent race both when firms are in symmetric and asymmetric positions.[3] Finally, their model is more suitable to study the effects of the information structure of the game on the incentive to innovate and cooperate.

1 Among them, there are Reinganum (1981), Fudenberg et al. (1983), Judd (1985), Harris and Vickers (1985), Grossman and Shapiro (1987).

2 Also Harris and Vickers (1987), and Grossman and Shapiro (1987) own this feature, though in a different context than our model (see below).

3 The bulk of patent race models deals with deals with only the symmetric case and have memoryless features, in which decisions at time t are independent on decisions at time $t-1$.

However, dynamic models of R&D obtain similar qualitative results: firms compete vigorously if they are close to one another, and the race degenerates into a monopoly if they are too far apart.

Our main departure from dynamic models of patent races is the assumption that firms can cooperate as well as compete. In this framework, we study the main determinants and effects of research joint ventures on the incentive to innovate and cooperate in patent races.

Specifically, we analyse the incentive for the formation of joint ventures and for their break-up in the course of the race, in relation to: (a) the relative as well as absolute position of the firms; (b) the degree of competition in the ex post market.

The main results are the following. (a) If firms are in the same position in the race in terms of acquired knowledge, they undertake a research joint venture (RJV) at the beginning of the race and break it up as they approach the finish line if competition is expected to prevail in the downstream market; if they can collude in the product market, firms make the innovation jointly. (b) An RJV is not formed when firms are in different positions in the race, unless firms are lagged by one step and cooperation makes an otherwise unprofitable project profitable. However, (c) cooperation reduces the speed of innovation with respect to a competitive R&D market.

The intuition behind these results is that firms in a similar position (in the race) cooperate to reduce the costs of the innovation. As they approach the finish line, however, the cost-reduction effect weakens and the incentive to gain a monopoly increases. The incentive increases in the expected degree of competition in the *ex post* market given joint discovery.

To test the theoretical results, we performed experiments on the behaviour of the players during the race. The outcomes of 86 races support the conclusions, although – unsurprisingly – the experimental results were not as clear-cut as the theory.

By contrast, Hey and Reynolds (1992), and Zizzo (2002) used experiments to test competitive models of R&D[4] and found only limited support to the theory.

Our approach is one of the few examples combining theoretical modelling and experimental evidence. Almost all the other papers in this area of research are restricted to one of these aspects.

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4 More precisely, Hey and Reynolds tested Fudenberg et al. (1983), and Zizzo Harris and Vickers (1987) models.

Significantly, our results overturn the main conclusions of the dynamic competitive models of R&D. By contrast to Fudenberg et al. (1983), Harris and Vickers (1985; 1987), and Grishagin et al. (2001), we found that if the option to cooperate is included, rent dissipation is unlikely to occur, because firms frequently undertake a cooperative agreement for the purpose of avoiding a disruptive patent race.

Cooperation in R&D reduces the cost of innovation but delays it. Recent decades have witnessed a proliferation of RJVs entailing the formation of a separate company. Surveys report that the number of new partnerships set up rose from 30–40 a year in the early 1970s, to over 600 in the 1980s and 1990s. During the early 1970s, about 80 percent were equity joint ventures, but in the mid-1990s more than 95 percent of technology partnerships did not involve equity investments. Information technology has been the prevalent area for partnership, followed by biotechnology and new materials (see Caloghirou et al., 2003).

The main reasons for RJVs are (reported to be): R&D cost sharing, reduction of R&D duplication, risk sharing, spillover internalisation, access of complementary resources and skills, technological learning. However, there is empirical evidence that firms may use RJVs to coordinate their interests regarding both existing product markets and the markets arising from the innovation (Scott, 1993, and Vonortas, 2000). We consider also the last issue in the paper.

This paper is organized as follows. Section 2 presents the model. Section 3 considers the R&D expenditure decision and Sect. 4 the incentive to cooperate in a patent race. Section 5 presents the experimental framework and Sect. 6 the experimental evidence. A final section offers some concluding remarks.

2 The Model

We consider a situation in which two firms are active in the same field of research to obtain a patent of value V, common to both firms.[5]

Following Fudenberg et al. (1983), we assume the R&D process is deterministic: there is a straight cause-and-effect relationship between

5 The two-firm case may be thought to be quite special, but it is not, considering that in the real world “the overwhelming majority of cooperative technology agreements have very few members – often as few as two” (Katz and Ordover, 1990, p. 173).

expenditure on the project and the amount of knowledge accumulated.[6] In addition, we assume the interest rate is zero. However, firms prefer an earlier date of innovation, due to an arbitrarily small rate of time preference or preferences on money and time.[7]

The discovery is a learning process that takes place through time, and we consider the making of decisions in the course of the discovery process. In particular, we assume that, at the beginning of each period, each firm knows the other's position, defined by the amount of knowledge already accumulated, and decides, independently or jointly, its R&D effort for the current period.

However, when firms compete in R&D, they decide how much expenditure to devote to the production of knowledge for the current period simultaneously and independently. This makes the game one of imperfect information, with a one-period information lag.[8]

In addition, we assume firms may revise their decisions during the race, depending on how they stand relative to their rival.

We denote by

$$w_i(t) \text{ firm's } i \text{ knowledge at time } t; \quad i = A, B$$

and

$$e_i(t) \text{ the effort of firm } i \text{ in period } t; \quad i = A, B.$$

6 As a matter of fact, discovery is a result of luck as well as of rational choices; therefore a stochastic R&D process assumption would be more appropriate. But, as one referee pointed out, modelling stochastic dynamic patent races is very hard. By contrast, a deterministic R&D process, although less realistic, allows to get clear-cut results. Moreover, it is reasonable to expect that other factors than uncertainty in the R&D process (the ones we consider in the paper) are lively to affect in a similar way the incentive to cooperate, whatever will be the nature of the R&D process. However, in stochastic R&D processes, firms may have, in addition to other reasons, an incentive to cooperate to avoid uncertainty due to the nature of the discovery process.

7 As Fudenberg et al. (1983) pointed out, explicit introduction of a probabilistic discovery and a positive interest rate would have no purpose, and we maintain their assumptions also to compare their results with ours.

8 This means that firms know their current position in the race but not their current decisions. A similar assumption is made by Fudenberg et al. (1983).

To simplify the analysis, following Fudenberg et al. (1983), we assume that possible effort levels are 0, 1, and 2, i.e., $e_i(t) \in \{0, 1, 2, \}$, $i = A, B$, with respective costs c_0, c_1 and c_2, $c_2 > c_1 > c_0$.

In addition, we denote by $k_i = N - w_i$ the units of additional knowledge for firm i in period t necessary to achieve the discovery. To avoid trivial results, we assume that firms cannot make the maximum possible effort throughout the race and still get positive profits[9]. Let $\overline{k}$ be the maximum amount of knowledge firms can accumulate by playing effort 2 with the race still having positive value, i.e., $\overline{k} < N$. It follows that for each firm it is profitable to make effort level 2 for a maximum of $\overline{k}/2$ times to get $V/2$, i.e.,

$$V/2 - (\overline{k}/2)c_2 > 0 > V/2 - (\overline{k}/2 + 1)c_2. \tag{D.1}$$

In addition, we assume:

$$c_2 > 2c_1. \tag{A.1}$$

Assumption (A.1) posits decreasing returns to scale in the R&D activity.

Either firm can successfully develop the innovation. If firms develop the innovation independently, we assume R&D activity is characterized by a multistage patent race for the acquisition of the prize V. Competition takes place in discrete time $t = 0, 1, \ldots, T$ and the discovery occurs with certainty when a given number of "units of knowledge", N, $N \in \{1, 2, \ldots\}$ is accumulated. The patent is awarded to the first firm that achieves knowledge level N. If the two firms achieve the discovery simultaneously, the prize is awarded to the firm with the higher level of knowledge. If they tie, they have equal probability of getting the prize.

As an alternative to competition, we assume that firms in each period can cooperate in the discovery process (this is the main departure from Fudenberg et al., 1983, and from Harris and Vickers, 1985; 1987).

Cooperation may take a variety of forms, ranging from simple coordination of R&D activity to perfect collusion both in the R&D and the product market. We assume it consists in an RJV, in which firms build

9 It is obvious that in a competitive R&D market both firms would always make the greatest effort in the attempt to win the race. A few experiments we performed with no constraint on the highest effort confirmed this intuition.

a common research laboratory and share the costs of R&D equally.[10] With cooperation, firms pool their acquired knowledge, so that, regardless of their previous positions, once they have joined the venture, the firms have the same amount of knowledge.[11] In addition, the results of the joint research are common knowledge to both firms.[12]

This form of cooperation produces advantages and disadvantages for firms. On the one hand, by eliminating duplication of effort, an RJV allows them to proceed to the discovery more efficiently. On the other hand, joint discovery reduces the possible gains of each firm, as monopoly is ruled out.

Indeed, the institution of a common lab to which both firms assign researchers is the condition that makes it easier to share knowledge, because researchers in the common lab plan subsequent experiments by

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10 Other forms of cooperation may be possible. However, notice that when there is no uncertainty in R&D activity cooperation never will be of information-sharing type only; because it is senseless to duplicate experiments. This may not be the case assuming uncertainty in the R&D process. In addition, in the sequential learning process we are considering, it is pointless to make experiments without waiting for the previous experiments' results. However, Tao and Wu (1997) show that this form of cooperation prevails when firms expect to compete in the downstream business. Analysis of the several forms of cooperation in R&D and in the product market are provided, among many others, by Kamien et al. (1992), and Silipo and Weiss (2005).

11 This implies the absence of moral hazard in making the venture. Notice that in an RJV with a common research lab and a sequential deterministic learning process, firms have no incentive to cheat on their acquired knowledge. This may not be the case with independent research labs and a stochastic learning process. For a recent analysis of the moral hazard problems arising in the formation of research joint ventures, see Veugelers and Kesteloot (1994), Pérez-Castrillo and Sandonís (1996), and Rosenkranz (1997).

12 We distinguish the incentive to cooperate from the incentive to reveal information after cooperation takes place. It is intuitive that the incentive to cooperate depends on each firm's stock of knowledge. In particular, it is unlikely that the leader of the race will cooperate if his advantage is not reflected in the division of the prize. However, *once the firms have decided to cooperate*, in the complete information and deterministic learning process we are considering, there is no reason to not fully reveal their information. After undertaking the venture, firms that would not fully share their knowledge should make no progress or they might duplicate experiments, because the venture should produce knowledge already acquired by some firm. By contrast, in the case of asymmetric information, Anton and Yao (1994; 2002) have shown that the greater the knowledge stock of one firm, the larger the payments it must receive to induce full disclosure of information.

comparing their acquired knowledge. However, if knowledge is observable, it is unlikely that cooperation could take place without full disclosure.

We assume that upon joint discovery, the firms share the prize equally. Even though this assumption may be thought unrealistic, it is not if we consider that the cooperative agreement is binding for only one period. Assume firms are uneven. In this case, thanks to the joint venture, the firm that is behind would equal the leader in knowledge and thus have an incentive to renegotiate the cooperative agreement in the following period, so as to incorporate the even position in the race.[13] Thus when firms operate in the same market, any cooperative agreement with unequal sharing of the prize is not renegotiation-proof.[14] However, it is also true that equal sharing reduces the leader's incentive to cooperate.[15]

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13 We have adopted this simplifying assumption in order to be able to compare our results with Fudenberg et al. (1983) and to facilitate the experiment by avoiding bargaining between players on the division of the prize.

14 Our assumptions are supported by Rosenkranz and Schmitz (2001), who analyze dynamic R&D alliances and show that change of the ownership structure over time may be an equilibrium phenomenon, because know-how, once released to the other firm, cannot be taken back, and is hence also available to the other firm in the second stage. Whether or not know-how has already been exchanged in the first stage thus affects optimal ownership structure in the second stage. Moreover, they show that some conclusions of static models do not extend to a dynamic framework. On the other hand, most papers in the incomplete contract literature, including D'Aspremont et al. (1998; 2000), Bhattacharya et al. (1992), and Castrillo and Sandonis (1996) consider only a static setting and cannot study the evolution of cooperation in the R&D race.

15 In other words, we assume the division of the prize is exogenously determined and firms are in a symmetric position in the *ex post* market. On the other hand, Fertshman and Kamien (1992) have shown that in a Nash bargaining game firms share the prize according to their acquired knowledge, i.e., if they tie, they share the prize equally and if one firm is ahead, it gets a larger share. Veugelers and Kesteloot (1997) found similar results on the incentive to cooperate in R&D among asymmetric partners. In addition, in a context of imperfect information, Pérez-Castrillo and Sandonís (1996) proved that this solution is also the one that induces firms to disclose their know-how. Finally, we proved in an earlier version of this paper, (Silipo, 2000) that allowing for asymmetric division of the prize enlarges the set of the parameters that make feasible cooperation among asymmetric firms.

Accordingly, we assume the cooperative agreement is binding for only one period, and firms revise their membership decision each period. Cooperative agreements are cost-less enforced.[16]

The description of the dynamic process may be characterised as follows.

In each period $t, t = 1, \ldots, T$, there are two stages.

Stage 1 : The firms decide sequentially whether to cooperate in R&D or to go it alone. Firm A moves first; it can choose one of the two options: cooperate in R&D or proceed by itself to the finishing line. Firm B moves second, and chooses whether or not to accept a cooperation proposal.[17]

Stage 2 : The firms decide the level of R&D effort either jointly or separately. If there is cooperation, firm A makes a proposal on the level of effort and firm B decides whether to accept or make a counter-proposal. Cooperation takes place only if the firms agree to cooperate and on the level of effort. If they fail to reach agreement on both matters, they decide simultaneously and independently the level of effort in current period.

Finally, firms must make a cooperation decision and a level of effort decision in each period of the race.

Suppose at time $t, t = 1, 2, ...T{-}1$; with T denoting the time of discovery, the position of the firms in terms of acquired knowledge is w_i for firm i and w_j for firm j; $i, j = A, B$.

The following game tree describes the decision process:
w_i is firm's i position at time t in terms of accumulated knowledge, and C (D) indicates the firms' decision to cooperate (compete) in the same period, $i = A, B$. At time t , firm i may be in the same position as its rival or in a different position. Without loss of generality, assume the same position and let $w_A = w_B$ be the amount of knowledge accumulated in the previous periods. The first decision firm i makes is whether to cooperate or conduct R&D independently.

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16 Notice that, in our case it is not relevant whether they make a binding agreement all through the race or for just one period, because there are no fixed costs related to the cooperative agreements. In this case, if the RJV is privately optimal, it is also socially optimal. By contrast, Vilasuso and Frascatore (2000) proved that if RJV's formation is costly, it is not always true that when it is profitable for firms to undertake a cooperative agreement it is also welfare improving. In particular, if RJV cost formation is low, an RJV is not privately optimal but it is socially optimal. If forming an RJV is very costly, social welfare is maximised when firms compete in R&D.

17 However, notice that it is irrelevant what firm moves first or is going to make first the membership.

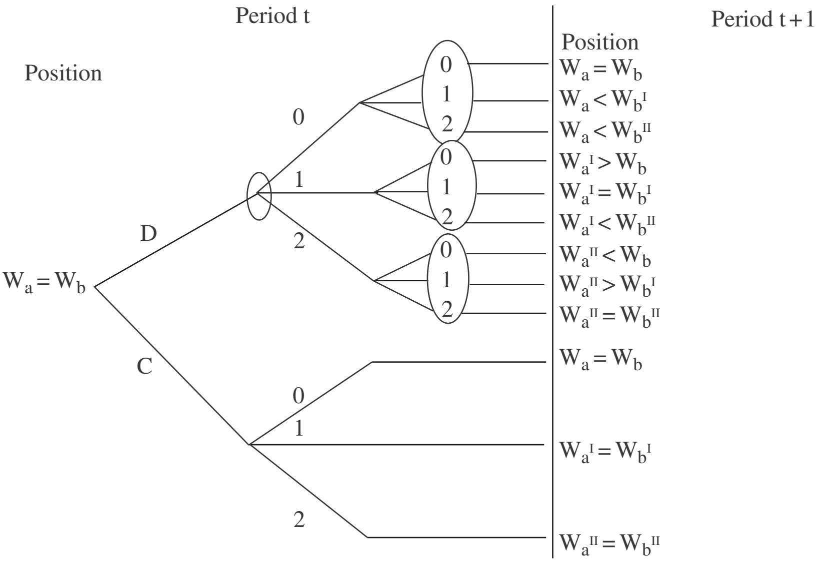

Fig. 1. The schedule of the game

Cooperation is characterised by a binding agreement in which firms exchange the knowledge acquired. So by cooperating, each firm acquires the amount of knowledge that is the highest amount one of the firms had accumulated previously.[18] If firms cooperate (branch C of Fig. 1), they jointly decide the amount of R&D expenditure (e^c) in the common research lab for the current period.[19] Whatever the amount of R&D performed in period *t*, it follows that, at the beginning of the next period, firms that cooperate are in the same position (represented by the three positions starting at the end of branch C in Fig. 1). Since the cooperative

18 This assumption reflects the deterministic nature of the R&D process, in which firms proceed to the discovery by accumulating additional bits of knowledge. Although many innovative processes are of this type, many others assume different features, especially when the discovery process is stochastic. In the latter case, the discovery may be also a by-product of R&D activity pursuing different aims. Moreover, uncertainty in R&D activity may also affect the incentive to cooperate (on this aspect see the discussion in Sect. 7).

19 With perfect information, an agreement, in which firms coordinate R&D activity conducted by each in its own lab and share the cost, would have the same features.

agreement is binding for only one period, they may now either continue to cooperate or break up the venture and pursue the aim independently.

If firm $i, i = A, B$, does not cooperate – which corresponds to branch D in Fig. 1 – the firms simultaneously and independently decide the amount of R&D expenditure for the current period. When firm *i* chooses its action, it does not know the rival's choice (represented by placing the nodes corresponding to firm *j*'s possible actions in the information set for firm *i*, i.e., the loops around the three nodes in Fig. 1). However, depending on the relative positions and the actions in period t, firm *i* may be even, ahead or behind of firm *j* at the beginning of the next period, and the game proceeds in this way until one or both firms achieve knowledge level *N*.

If firms compete in R&D, it follows that firm *i*'s expected profit at time *t*, when it still has k_i units of knowledge to acquire and firm *j* has k_j steps to go is

$$E\Pi_i^{nc}(k_i, k_j) = \alpha_i^{nc}(k_i, k_j)V - \sum_{\ell=n}^{1} c(e_{i,\ell}^{nc}(k_{i,\ell}, k_{j,\ell})), \tag{1}$$

where $i, j = A, B$, $\alpha_i^{nc}T$ is firm *i*' s expected reward when it is k_i units and firm *j* is k_j units of knowledge away from the discovery, which is unknown until the game is over; $\alpha_i^{nc} \in \{0, 1/2, 1\}$ depending on whether firm *i* loses, ties, or wins the race; *n* is the number of periods necessary for firm *i* to achieve the discovery when it plays $e_{i,\ell}^{nc}(k_{i,\ell}, k_{j,\ell}), \ell = n, \ldots, 1$ up to the discovery, sustaining the cost $\sum_{\ell=n}^{1} c(e_{i,\ell}^{nc}(k_{i,\ell}, k_{j,\ell}))$. We assume that the cost functions of the firms are equal.

By contrast, if the firms cooperate, firm *i*'s expected profit at time *t* when it has k_i and firm *j* has k_j steps to go and firms undertake an RJV is[20]

$$E\Pi_i^{c}(k_i, k_j) = \alpha_i^{c}(k_i, k_j)\gamma V - \sum_{\ell=n}^{1} c(e_{i,\ell}^{c}(\hat{k}_\ell)/2, \tag{2}$$

where α_i^c now is the share of the reward firm *i* gets in the cooperative agreement. By the previous assumption, we have $\alpha_i^c = \frac{1}{2}, i = A, B$.

20 Here, the expectation term in the profit function (2) comes from the fact that firms do not know whether the cooperative agreement will last until the game is over.

In addition, we assume the expected revenue in the case of joint discovery depends on the degree of competition in the *ex post* product market (γ). The latter may assume a variety of potential situations, ranging from collusion to perfect competition.

Left alone, cooperative firms would like to collude in the product market (i.e., $\gamma = 1$). However, if the antitrust authority bans collusion, firms that make the discovery jointly will have to compete in the product market, (i.e., $\gamma < 1$)[21], Moreover, there exists $\tilde{\gamma}$, a value of γ, such that $E\Pi_i^c(k_i, k_j) = 0$. $\hat{k}_\ell = \min\{ki, kj\}$ is the units of knowledge to discovery when they cooperate and play $e_{i,\ell}^c(\hat{k}_\ell), \ell = n, \ldots, 1$ up to the discovery, sustaining the cost $\sum_{\ell=n}^{1} c(e_{i,\ell}^c(\hat{k}_\ell))/2$. We assume that the member firms share the cost of the R&D project equally.

Notice that $E\Pi_i^{nc}(k,k) > E\Pi_i^{nc}(k+j,k)$, but $E\Pi_i^{nc}(k,k) \geq (\leq)$ $E\Pi_i^c(k,k)$, $i = A, B$, depending on whether the expected revenue reduction is higher (lower) than the cost reduction when firms make a joint venture. The main aim in this paper is to establish the circumstances in which an RJV will be formed and those in which a cooperative agreement collapses.

The *solution concept* is that of subgame perfect Nash equilibrium, with respect to the type of game to play and the amount of R&D effort. As usual, the equilibrium of the game is obtained by backward induction.

The model considers a duopoly patent race with no uncertainty in the R&D process but with imperfect information. By conducting R&D activity, firms accumulate knowledge and thus approach the discovery. In every period, firms decide whether or not to cooperate. In the case of cooperation, they are in the same position in the race. In the case of competition each proceeds to the discovery on its own. Depending on whether they cooperate or compete, firms either make the discovery jointly (and in this case they can either collude or compete in the downstream market) or finish the race one after the other (the winner gets the monopoly profit, the loser gets nothing). In the following sections, we first study the amount of R&D expenditure under the two regimes and then we consider the evolution of cooperation in the discovery process.

21 Notice that the degree of appropriability of the prize also depends on other factors, such as the degree of spillovers in the product market. So, an alternative interpretation of the model may be how the incentive to cooperate in a patent race is affected by the degree of spillovers in the *ex post* market.

3 The R&D Expenditure Decision

We first consider the solution to the second stage game. Assume firms are k steps from the discovery and they form an RJV. The optimal amount of effort made by the venture is stated in the following:

Lemma 1: In a duopoly R&D market, the optimal level of effort for an RJV is $e^c = 1$ whatever the distance of the firms from the finish line or the positions of the firms in the race.

Proof: Notice that, whatever the previous positions of the firms, when they cooperate they have the same amount of knowledge. Thus the optimal level of effort is given by solving the following problem:

$$\max_{e^c_{i,\ell}} E\Pi^c_i(k_i, k_j) = \max_{e^c_{i,\ell}} \left[\alpha^c_i(k_i, k_j)\gamma V - \sum_{\ell=n}^{1} c(e^c_{i,\ell}(\hat{k}_\ell)/2 \right] \qquad (3)$$

for $i = A, B$, and $n = 1, \ldots, N$.

The proof is obtained by backward induction. First, notice that when firms cooperate they are in a symmetric position; i.e., $k_i = k_j = \hat{k}$. Assume they are in the last period of the game (i.e., $n = 1$) and there is one step to go (i.e., $\hat{k}_\ell = 1$). Since only one more step is needed, it follows that playing 1 is sufficient to get the patent in the current period: playing 2 is more than requested to get the patent in current period and playing 0 delays the innovation. By the assumption of "impatience", the firms prefer to get the innovation earlier,[22] so we conclude that the optimal level of effort in the last period is 1, and each firm contributes by $c_1/2$ to the venture.

Now assume that in the last period firms are two steps away from the discovery. By the previous argument, firms do not play 0. So we compare the other two options. If they play 1 they get the patent in the subsequent period; if they play 2 they get the patent in current period. But the cost of

22 This may not be the case if the firms lose current profits because of the innovation. In this case, the firms operating in a duopoly product market can undertake an RJV to delay the innovation. However, such strategic delay may be more difficult if more than two firms are active in the same market and the RJV is not worldwide.

getting the patent one period earlier is $c_2 – c_1$, and the benefit, by the assumption made before, is equal to the arbitrarily small rate of time preference. So we conclude that it is optimal for the firms to play 1 even when there are two steps to go. Notice that the cost of making the discovery earlier increases with the number of steps to go. Therefore, a fortiori the result holds when we are more than two steps away (i.e., $n \geq 2$). □

This result follows from the fact that when firms cooperate and the discount factor is arbitrarily small, the main factor affecting expenditure is the R&D technology.[23] Since R&D costs are convex, it is more efficient to proceed at low speed, regardless of distance from the finish line.

By contrast, in a competitive R&D market, the speed of innovation is characterised as follows (see Fudenberg et al., 1983).

If both firms are less than $\overline{k}$ steps away from the discovery and are even, they both play 2. If a firm is ahead by 1 step, the leader plays a mixed strategy on [1,2] and the follower a mixed strategy on [0, 2]. Finally, if the leader is more than 1 step ahead, the race degenerates into a monopoly. The leader plays 1 and the follower drops out.[24]

If both firms are more than $\overline{k}$ steps away from the discovery and are even: both play the mixed strategy on the pure strategies [0, 1, 2]. If one firm leads by one or more steps, the race degenerates into a monopoly. The firm that is ahead plays 1 and the follower plays 0.

Based on these results, Fudenberg et al. (1983) concluded that, if firms start with equal experience, the race will be characterised by "a burst of R&D followed by the eventual emergence of a monopolist. The initial competition for the patent on average dissipates the monopoly profit" (p. 15).

Comparing cooperation with competition, we can conclude that where firms cooperate, rent is never dissipated. Cooperation reduces the cost of innovation but increases the length of time necessary to achieve it. Thus welfare comparison depends on the relative weight of time and costs in the discovery process.

However, the crucial question is the definition of the circumstances in which firms form an RJV or compete.

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23 Recall that in the present paper we do not consider uncertainty and spillovers.

24 The last result holds also when the leader is less than $\overline{k}$ steps and the follower is more than $\overline{k}$ steps from the discovery.

4 The Membership Decision and the Evolution of Cooperation

Broadly speaking, Eq. (3) shows that the incentive to form an RJV depends on the division of the prize (α), the degree of competition in the ex post market (γ), the form of the R&D cost function and the relative position of the firms in the race.

By forming an RJV firms save on costs and can eliminate uncertainty over the outcome of the patent race. The disadvantage is that they must share the reward and may have to be competitors in the downstream market.

We therefore consider the incentive to form and to break up an RJV in relation to the degree of competition in the *ex post* market and the position of the firms in the race.[25] First, we consider the case in which firms are tied.

4.1 The Case of Symmetry

We assume that the firms are even in the patent race and consider the incentive to cooperate in R&D. Firms' behaviour is then characterised by the following proposition:

Proposition 1: If firms are in the same position in the race and they split the reward equally, they will form an RJV at the start of the race. In addition, there exists a critical level of the degree of competition in the *ex post* market (γ') such that firms make the discovery jointly if $\gamma > \gamma'$ but break up the venture sometime before the end of the race if $\gamma < \gamma'$.

Proof: See Appendix 1.
From Proposition 1 above, Corollary 1 follows.

Corollary 1: The less competition in the ex post market, the higher the number of periods in which evenly placed firms cooperate during the patent race.

Proof. This is straightforward from the proof of Proposition 1.

The main conclusion is that evenly placed firms cooperate throughout the race if the degree of competition in the ex post market is low ($\gamma > \gamma'$). Furthermore, for intermediate values of the degree of market competition

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25 Very recently, Caloghirou et al. (2003) have reported that all the above aspects are significant determinants of firms' incentive to form RJVs.

$\tilde{\gamma} < \gamma < \gamma'$ such firms will cooperate at the start and will break the cooperative agreement at some stage before the end of the race. Finally, if the value of the race is positive and competition will prevail after joint discovery, firms will never cooperate in R&D. However, if the value of the race is negative, there may be cooperation, provided that it can transform a project of negative value into one with positive expected profit.

The intuition implied by this result is that firms, that are evenly placed, dissipate the gain from innovation if they engage in a disruptive race for the full prize. Cooperation in R&D reduces the costs of the innovation and eliminates uncertainty over victory (there is joint discovery). However, if they expect intense competition in the *ex post* market, they break up the venture as they approach the finish line and seek to appropriate the full prize. Moreover, if competition in the *ex post* market is expected to dissipate the entire rent from the innovation ($\gamma = \tilde{\gamma}$), evenly placed firms will never cooperate, preferring competition on R&D in hopes of becoming a monopolist (recall that if firms finish the race at almost the same time, the prize is allocated randomly).

However, if they can collude in the product market their interests do not conflict and they proceed jointly to the discovery, because each firm eliminates any uncertainty on the possibility to win the race.[26]

4.2 The Case of Asymmetry

Let us now consider the incentive to cooperate for firms that do not start out even in the race. We retain the assumption that firms share the prize equally. The leader thus saves on costs by cooperating but loses his lead, because he must share his knowledge with his rival, putting the two on an equal footing. In this case, the leader must weigh the advantages of cooperation (lower R&D cost) against the disadvantages (no monopoly in the ex post market). By contrast, it is intuitive to expect that the follower stands to gain more from the cooperative agreement than in the case of symmetry and would be more willing to cooperate. The following proposition states the incentive of the leader to cooperate.

26 This implies that firms operating in different industries have a greater incentive to cooperate in a patent race than firms operating in the same industry.

Proposition 2: Assume the leader is one step ahead and the firms share the prize equally. An RJV is not formed if the value of the race is positive. However, if γ is sufficiently high, and the value of the race at the outset is negative, and the R&D technology is sufficiently convex (i.e., $\bar{k}(c_2 - c_1) > V - jc_1$), an RJV will be formed at the start and will last throughout the race. However, an RJV is never formed if the leader is more than one step ahead.

Proof: See Appendix 2.

Thus we conclude that a leader, who is two or more steps ahead, never undertakes a cooperative agreement if the two firms split the prize equally. This result still holds when firms are only one step apart if the value of the race is positive. When the latter is negative, however, if the saving from cooperation is large enough, an RJV will be formed even when the leader is only one step ahead and the prize is split equally, as long as the firms can collude in the *ex post* market.

The explanation lies in the fact that when the leader is one step ahead, he loses his lead by cooperating. If the value of the race is positive, there is an advantage in winning, so the leader has no incentive to cooperate, although, in some stages, he must play the highest effort level to maintain his leadership. If the value of the race is negative, and the R&D technology is convex, cooperation may turn an otherwise unprofitable R&D project into a profitable one, thanks to cost-cutting through the RJV.[27] By contrast, if the leader is more than one step ahead, the reduction in costs never outweighs the loss of expected revenue, because the leader can secure the patent even with a low level of effort throughout the race.

Finally, comparing the asymmetric and symmetric cases, we conclude that under asymmetry an RJV can be formed only when the value of the race is negative, whereas under symmetry it may also occur when the value is positive.

27 Scott (1996) provided evidence that cooperation fosters new research that would not have been initiated otherwise.

From Propositions 1 and 2, we have the following corollary:

Corollary 2: The longer the race, the greater the incentive to cooperate.

Proof: The proof is straightforward from (6) and (11.1).

From Corollary 2, it follows that cooperation, when it is found, always comes in the early stages. On the other hand, from Proposition 1 and 2, it follows that, if the agreement is broken, it will never be reconsidered.

On this basis, we can characterise firms' behaviour when they can cooperate and when they compete. Optimal behaviour is characterised as follows.

If both firms must accumulate $k_i > \bar{k}, \quad i = A, B$, units of knowledge to the discovery, and

(1) Firms are tied:
  (i) they cooperate in R&D and play 1;
  (i.1) if they can collude in the product market, cooperation will continue to the end of the race;
  (i.2) if competition will prevail in the product market, the cooperative agreement will break down at some stage before the end of the race.
(2) One firm is ahead by 1 step:
  (i) if the value of the race at the outset is positive, the race degenerates into a monopoly.
  (ii) If the value of the race is negative, the cost saving due to cooperation is high, and firms can collude in the product market, the leader cooperates throughout the race.
(3) One firm is ahead by more than 1 step:
  (i) the race degenerates into a monopoly. The leader plays 1 and the follower drops out.

The same result also holds for $k < \bar{k}$.

Notice that in a duopoly patent race with cooperating firms, rent dissipation never occurs. Rent dissipation is more likely when firms are asymmetrically placed, as, in order to maintain his leadership, the leader must play the highest effort.

We performed some experiments to test whether these theoretical conclusions are supported by actual behavior.

5. The Design of the Experiments

There is good reason for experimental investigation into cooperation in patent races. First, there is very little empirical evidence on the evolution of cooperation in R&D. Second and most important, the empirical evidence is not suitable to test our theoretical hypotheses. But experiments can be designed so as to reproduce conditions similar to the theoretical model in the "laboratory".

Like our theoretical model, in the experiment we assume that two subjects are involved in a patent race for a prize. The winner is the first firm to accumulate 30 "units of knowledge". In each period players may accumulate 0, 1, or 2 units of knowledge, which cost respectively nil, \$ 0.44 cents and \$ 1.11: that is, we assume increasing marginal costs of knowledge acquisition.

However, to conform to our theoretical assumptions, in our experimental game players cannot always make the highest effort.[28] Specifically, no player can play 2 more than 10 times.[29]

The winner, the first player to accumulate 30 units of knowledge, gets the profit $\Pi_{nc} = V - \textit{total costs}$ and the loser gets nothing. If both players independently accumulate 30 units of knowledge in the same period, the computer chooses the winner randomly.[30]

If the two players cooperate from the outset and make the discovery jointly, each player gets the profit $\Pi_{nc} = (V - \textit{total costs})/2$. So, total costs as well as profits depend on the course of the race, and they are the sum of the costs incurred individually and half of those incurred jointly.

We ran half the games with a value of the prize $V =$ \$ 18.97, the other half of \$ 37.94 dollars. These two settings represented an ex post market characterised respectively by competition and collusion upon joint discovery. Thus, players starting in the same position and playing the Nash equilibrium throughout would get an expected profit of \$ 3.00 if $V =$ \$ 18.97 and \$ 12.27 if $V =$ \$ 37.94. As in the theoretical model, in each period each player must make a cooperation decision and a level of effort

28 Otherwise, players would probably always play the highest effort. Indeed, the latter was the case in the five races I ran with no constraint on the number of times players could play two.

29 Hence, the total amount of knowledge each player can accumulate by playing 2 is $\bar{k} = 20$.

30 If they reach the finish line at the same time but one player has accumulated more knowledge, he is the winner.

decision. One player moves first. Let player A move first. If player A wants to cooperate, he makes a proposal to the other player, expressing willingness to cooperate and suggesting a level of effort. Cooperation takes place when the players agree on both these decisions: otherwise competition prevails.

With cooperation, both players take the same position in the race, namely the highest level of knowledge acquired so far by either of them. Alternatively, if a player does not want to cooperate in the current period, the players make their effort decisions simultaneously and independently. So as in the theoretical model, the experiment is one of imperfect information.

Once both players have made their decisions, the computer updates their relative position in the race, and the current period ends. The experiment proceeds in the same way for subsequent periods until the end of the race.

At all times, players could check the main parameters on the screen, i.e., the knowledge accumulated by both players, the costs sustained, the number of times they could still play 2.

The main features of the experiments are summarised in Table 1 below.

Table 1

Number of races	86
Number of participants	2 in each race
Value of the prize	\$ 18.97 or \$ 37.94
Possible effort levels to be made	0, 1 or 2
Cost of effort	$c_0 = \$ 0$; $c_1 = \$ 0.44$; $c_2 = \$ 1.11$
Units of knowledge to be accumulated for the discovery	30
Maximum number of times each player can play 2	10

The experiments were run in March 2000 and November 2003 at the University of Calabria – Cosenza (Italy), and involved 172 subjects.[31] We told the participants that the computer at the beginning of the section randomly assigned one of the other persons in the room as their opponent,

31 The project under which the experiments were performed was funded by the Italian Ministry for Universities and Scientific Research and coordinated by John Hey. The programme for the experiments was written by using *z*-Three (Zurich Toolbox for Readymade Experiments), and it is available from the author upon request.

but they were not told which. We also told them they were allowed to play only one race. Out of the 86 races, half had a prize of $ 18.97 and half a prize of $ 37.94.

For each value of the prize, we ran 19 races with both players starting in the same position (0,0), another 19 races in which one player had an initial advantage of one (0,1), plus 5 in which one player had an initial advantage of two (0,2). The reason we performed only five experiments with initial position (0,2) is that in this case the result should be obvious: the leader would never be willing to cooperate or to lose the race. Players learned their initial positions only once the game had started; they could not choose which race to run.

The experiments were run in four sessions, the first three with 26 simultaneous races, involving all the possible values of the parameters, and the fourth with only eight races. We recorded not only the race results but each decision and outcome for all players at every stage of every race. Thus, we have a large body of experimental evidence that allows us to investigate whether actual behaviour is consistent with the optimal strategies reported above.

6 The Experimental Evidence

We can now present the main results of the experiments against the backdrop of the theoretical conclusions. Subsequently, we examine the experimental evidence in detail for further insight into firms' behaviour.

Before to do this, it may be worthwhile to present the main results of the races.

Out of 19 races starting in the (0,0) position, only 5 ended with joint discovery when the prize was low ($ 18.97); while with a large prize ($ 37.94) 12 out 19 did.

Thus, the evidence supports our theoretical conclusion that joint discovery is more likely to occur when firms can collude in the product market.

However, counter to the theory, Fig. 2 shows joint discovery even when players started unequally. Out of 19 races with initial position (0,1), 7 ended with joint discovery in the low-prize case and 5 in the high-prize case. Note that here the incentive for joint discovery is lower, the greater the prize.

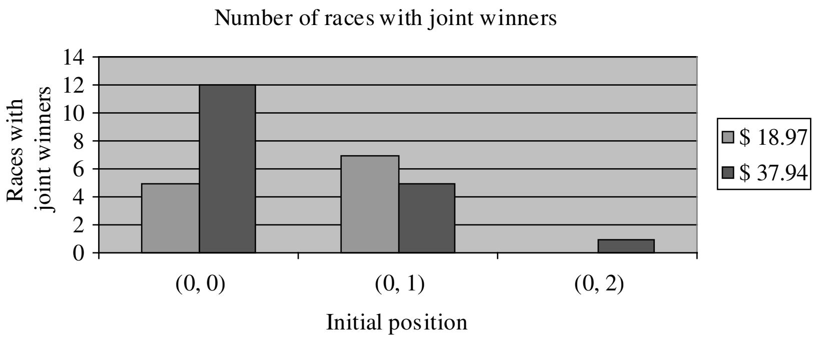

Fig. 2. Number of races with joint winners

Finally, the experimental races broadly support our theoretical results for the initial position (0,2). Joint discovery never happened for the small prize, and only once for the large prize (see Fig. 2), although, in this case again, a few players made unexpected decisions (see Fig. 6 below).

For the statistical investigation of players' individual choices, we first built up a panel covering all the races and all the decisions made by the players in each race.[32] Then we tested our assumptions using a random effects probit model, with which we can take account of both cross section and the time-dimension of the variables.

However, in the regressions that compare only the outcomes of the races for each subject (Eqs. (2), (3) and (4) in Table 3 below)[33], we used probit model estimation methods.

In some regressions, we have observations for each period, as what we are interested in is the player's behaviour in the course of the race; in other regressions we are interested in the outcome of the race in relation to players' characteristics (leader, follower, etc.), defined by their initial conditions and average positions.

To make clear whether the data analysis is systematic enough in relation to the theoretical conclusions, Table 3 reports both the theoretical assumptions and the experimental evidence.

We used the variables listed in Table 2 below to test the main hypotheses.

The main conclusions of this analysis are reported in Table 3.

32 Our dataset on individual choices contains 3676 observations.
33 Notably, in these regressions the time-dimension of the variables is absent.

Table 2

EFF	Player's level of effort (0,1,2)
AEFF	Player's average effort in the race
D1	Dummy =1 if cooperation occurs; 0 otherwise
D2	Dummy =1 if the player starts even; 0 otherwise
D3	Dummy =1 if the prize high, 0 otherwise
D4	Dummy =1 if single winner of the race, 0 otherwise
D5	Dummy =1 if joint winner of the race; 0 otherwise
W	Units of knowledge still to accumulate to get 30 units
INT1	Interaction term D3*D8
INT2	Interaction term D3*W
D6	Dummy=1 if the player is a leader, 0 otherwise
D7	Dummy=1 if the player is a follower, 0 otherwise
D8	Dummy=1 if the player is even, 0 otherwise
D9	Dummy=1 if the player makes a proposal to cooperate, 0 otherwise
D10	Dummy=1 if the race starts in the (0,2) initial position, 0 otherwise
D11	Dummy=1 if the race starts in the (0,1) initial position, 0 otherwise
AH	Percentage of periods in which the player is ahead in the race
EV	Percentage of periods in which the player is even in the race

Equation (1) in Table 3 tests the results on level of effort. Lemma 1 states that, if firms cooperate, the level of effort is 1. Fudenberg et al. (1983) proved that where there is competition, effort is likely to be greater than 1. The estimations show that when players cooperate there is lower probability of making the greatest effort. Furthermore, leaders are more likely than trailers to make a greater effort.[34] Finally, the closer the end of the race, the greater the probability of greatest effort.

In short, the statistical investigation supports the model's main conclusion on level of effort under the two R&D conditions.

Next we performed some tests on the incentive to cooperate.

Proposition 1 states that firms starting in the same position win jointly if the prize is large, individually if it is small.

Equation (2) in Table 3 shows that an even starting position has no explanatory power concerning the probability of winning jointly (although the coefficient of D2 has the expected sign). However, there

34 The dummy variable D6, which captures whether the player is ahead or not, has a positive impact on effort.

Table 3. Theoretical assumptions and econometric results

Theoretical assumptions	***H1: EFF=1 if coop; EFF=1 if nocoop.***	***H2: In (0,0) initial pos. races ⟶ JW (SW) if prize high (low).***		***H3: In (0,1) and (0,2) initial pos. races ⟶ SW***	***H4: If same position ⟶ cooperation, if different position ⟶ competition. H5: If prize low, even firms break coop as they approach the end..***		
				Estimations			
Dependent	**Eq. (1) EFF**	**Eq. (2) D5**	**Eq. (3) D5**	**Eq. (4) D4**	**Eq. (5) D1**	**Eq. (6) D1**	**Eq. (7) D9**
Cons.	2.4662 *(0.0000)*	−3.4540 *(0.0000)*	−0.7353 *(0.0000)*	−2.6088 *(0.0016)*	−2.3841 *(0.0000)*	.2.4040 *(0.0000)*	−0.6630 *(0.0000)*
D1	−0.1196 *(0.0054)*						
D2		0.0066 *(0.9799)*					
D3		0.4940 *(0.0612)*	0.6752 *(0.0023)*	−0.3038 *(0.2139)*	0.7237 *(0.0000)*	0.5842 *(0.1343)*	0.1962 *(0.0989)*
D6	0.3021 *(0.0000)*						−0.8642 *(0.0000)*
D8					2.5067 *(0.0000)*	2.2380 *(0.0000)*	1.2837 *(0.0000)*
D10			−0.9843 *(0.0225)*	0.2637 *(0.4341)*			
D11			0.2547 *(0.2676)*	−0.1354 *(0.6093)*			
AEFF				1.4135 *(0.0271)*			
W	−0.0347 *(0.0000)*				0.0054 *(0.1216)*	0.0211 *(0.0000)*	0.0243 *(0.0000)*
INT1						1.1645 *(0.0003)*	
INT2						−0.0482 *(0.0000)*	
EV		4.5735 *(0.0000)*					
AH				2.2207 *(0.0000)*			
Mu **(1)**	0.1451 *(0.0000)*						
Mu **(2)**	2.3179 *(0.0000)*						
Mu **(3)**	2.8931 *(0.0000)*						
Log likelihood	−3867.80	−62.22	−90.33	−77.09	−950.67	−1380.902	−1046.32
Obs.	3676	172	172	172	3676	3676	3676

In brackets, p-values of Z-statistic.

For the explanation of all variables used in the regressions see Table 2.

Equation (1), estimated by using a random effects ordered probability model, is: EFF = f (D1, D6, W);

Equations (2), (3) and (4), estimated by using a binomial probit model, are respectively: D5=F (D2, D3, EV); D5 = F (D3, D10, D11); D4 = F (D3, D10, D11, AEFF, AH). Equations (5), (6) and (7), estimated by using a random effects binary probit model, are respectively: D1 = F(D3, D8, W); D1 = F(D3, D8, W, INT1, INT2) and D9 = F(D3, D6, D8, W).

results that the relevant variable is not the initial position (variable D2 in Eq. (2) is not statistically significant) but the percentage of times during the race at which players are even (EV).[35] The latter regressor does have a positive impact on the probability of winning jointly.

In short, relative position during the race appears to be more important than the initial conditions in determining the outcome.

Finally, and most important, when the initial position is even, then the larger the prize, the higher the probability of joint victory. These results thus also support the main conclusion of Proposition 1.

To inquire into why the initial position lacks explanatory power, we took dummies D10 and D11 as regressors. Equation (3) shows that initial position (0,1) has no effect compared with an even position.[36] However, in line with the theoretical conclusions, initial position (0,2) does significantly reduce the probability of joint victory. Thus, the lack of significance of the even start depends on the fact that players starting in the (0,0) and in the (0,1) initial positions have similar behavior.

Using Eq. (4), we investigated whether an initial advantage has a positive impact on the probability of winning. The results (Table 3) show that dummies D10 and D11, which capture an initial advantage, have no significant impact on the probability of victory (neither regressor is statistically significant). This result conflicts with our theoretical conclusions.

However, the probability of a single player's winning is positively affected by the percentage of periods in which that player is ahead and by the average effort he makes during the race.

Finally, comparing Eqs. (2) and (4), notice that the value of the prize is not statistically significant for individual victory but is significant for winning jointly.

Next, we considered the incentive to cooperate in relation to the players' relative position. On a theoretical basis, we would expect that: (1) if players are in the same position, they cooperate and, if they are in different positions, they compete; (2) players, who cooperate, cease

35 Notice that Eq. (1) is based on estimation of individual choices all through the races (the database includes 3676 observations); by contrast Eqs. (2) and (3) have been estimated on a player base (each equation includes 172 observations).

36 Like D2, D11 is not statistically significant with respect to the probability of winning jointly.

cooperation as they approach the end of the race if the prize is low but make the discovery jointly if it is high.

Equation 5 gives the results concerning the incentive to cooperate during the race. Players, who are even, are more likely to cooperate through the discovery process. So an even position increases not only the probability of winning jointly, but also the incentive to cooperate. Moreover, the probability of cooperating is also affected positively by the value of the prize. Finally, the coefficient of W, except for the expected sign, is not statistically significant.

To seek insight into question (2) above, we considered the joint effect of the prize value and the even position in the race (INT1) on the incentive to cooperate; and the joint effect of the prize value and W (INT2) on the incentive to cooperate. The results (Eq. (6) in Table 3) show that for even players the probability of cooperation throughout the race is higher when the prize is large (the coefficient of INT1 is positive). But as players approach the end of the race, the probability is greater when the prize is large (the coefficient of INT2 is negative). Both results support conclusion (2) above.

Finally, we considered the main determinants of the proposal to make a cooperative agreement during the race.[37] The results are reported in Eq. (7) in Table 3. Players, who are even, are more likely to propose cooperation. One, who is definitely in the lead, is less likely to propose a pact. Moreover, as in Eqs. (2) and (5), the incentive to cooperate is affected positively by a larger prize value.

Finally, Eq. (7) shows that the further away they are from the finish line, the more likely players are to propose an agreement (the sign of W is positive).

In overall, not only the theoretical model but also the statistical estimations indicate that cooperation is greater if players are evenly matched and if the prize is large. When there is cooperation, players reduce their levels of effort.

Thus, the experimental evidence supports the main theoretical indications of the model concerning the incentive to cooperate and the effort levels, though many inconsistencies did emerge. This suggests that many of the subjects had trouble grasping the relevant costs and benefits. We

37 Notice that the proposal to cooperate may differ from the cooperative agreement, as proposals may not match or players may disagree on level of effort.

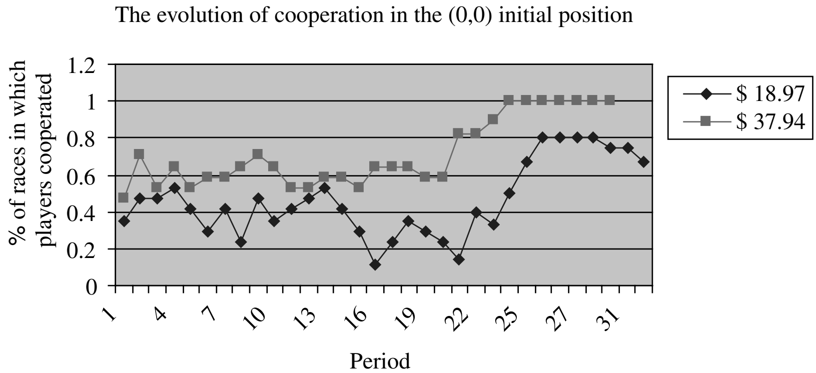

Fig. 3. The evolution of cooperation in the (0,0) initial position

might expect to find a better fit with the model in the case of more experienced players.

To get more insight into players' behaviour, we now consider the evolution of cooperation during the course of the race.

Figure 3 shows the evolution of cooperation when players start in the (0,0) position.

For firms starting even, the theoretical model predicts cooperation throughout the race for the large prize and cooperation in the early stages followed by competition when the prize is small. The experimental evidence confirms this, albeit less clearly in the latter than in the former case. Recall that, according to the model, evenly matched firms always want to cooperate in the early stages, but this is not so in our experiments. In 6 of the 38 races in the (0,0) initial position, the players never cooperated at all;[38] in 15 of them, they cooperated throughout the whole game. Finally, when players started even, cooperation broke down in the later stages in 11 out of the 14 races in which there was cooperation for a small prize. When the prize was large, cooperation broke down in only 5 of 16 races.

38 This could be due to the fact that players may value the prize differently in subjective terms; what is a large prize for one player may not be for the other.

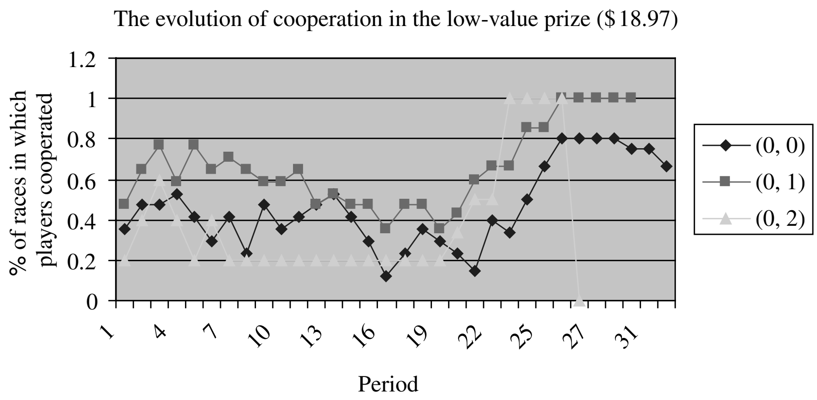

Fig. 4. The evolution of cooperation in the low-value prize ($ 18.97)

The experimental results are messier than the theoretical hypotheses, but they do appear to support the thesis that evenly matched firms tend to break off cooperation more often when the prize is small.[39]

However, Fig. 3 shows that the incentive to cooperate during the race is greater in the high- than in the low-prize case. The test reported in Table 4 confirms the significant divergence in average behavior during the race with respect to the incentive to cooperate.[40]

Next, we considered the incentive to cooperate during the race when the initial position is different. On a theoretical basis, we would expect no cooperation at all in this case. But Figs. 4 and 5 show that cooperation also occurred among uneven players.

However, as in the model, when the prize is large (Fig. 5), the incentive to cooperate is greater when players start out even than when one has an initial advantage. But this result is not general. Rather, the opposite holds for small prizes when we compare the initial positions (0,0) and (0,1), see Fig. 4.

39 In the (0,1) initial position, players terminate cooperation 8 of 15 times for the small prize and 10 of 13 for the large one.

40 See the result reported in the first row of Fig. 4.

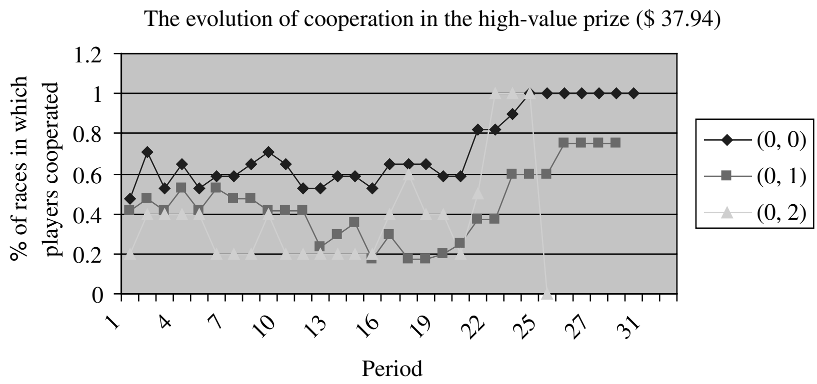

Fig. 5. The evolution of cooperation in the high-value prize ($ 37.94)

Table 4. Tests on differences between the average behaviour of the players during the race

		Small prize			Large prize		
		(0,0)	(0,1)	(0,2)	(0,0)	(0,1)	(0,2)
Small prize	(0,0)				−5,219 *0,0000*		
	(0,1)	−3,947 *0,0000*					
	(0,2)	1,185 *0,2420*	4,182 *0,0000*				
Large prize	(0,0)	−5,219 *0,0000*					
	(0,1)				5,940 *0,0000*		
	(0,2)				5,316 *0,0000*	0,892 *0,3780*	

Furthermore, differences in behaviour during the race between even and uneven initial positions are clearer-cut for the large than for the small prize.[41]

41 When the prize is large the difference between the average incentives to cooperate is 0.28 when we compare races starting in the (0,0) and (0,1) initial positions, and 0.34 when we compare races starting in the (0,0) and (0,2) initial positions. By contrast, for the small-prize case the corresponding differences are −0.21 and 0.08.

The tests on differences between the average incentives to cooperate (Table 4) show that differences between even and uneven initial positions are always significant in the large-prize case and only once in the small-prize case.[42]

In any event, all the figures show players changing behaviour more often than our model would predict.

7 Conclusions

In a simplified model with only two firms involved in a patent race, we studied the evolution of cooperation in the course of the race and the speed of innovation under the cooperative and competitive R&D regimes.

The main theoretical conclusions are that the race is mostly characterised by competition if the firms are in different starting positions and by cooperation if they start out even. In the latter case, they make the discovery jointly if they can collude in the downstream product market and break up their joint venture in the last stages if they must compete. Firms involved in a cooperative research agreement proceed at lower speed.

Therefore, unlike Fudenberg et al. (1983), and Harris and Vickers (1985), who found that the race is characterised by vigorous competition if the firms are even, we find that, when firms are evenly matched, they make cooperative research agreements and rent dissipation never occurs. Dissipation is likely when firms are unevenly positioned.

Experimental evidence supports our theoretical conclusions, although, as in other experiments testing competitive models of R&D (see Hey and Reynolds, 1992, and Zizzo, 2002), in some races the subjects did rather worse than predicted.

Overall, both the theoretical model and the statistical estimates indicate more cooperation when players are evenly matched and when the prize is large. When there is cooperation, players reduce their levels of effort. Also, for firms starting even, the theoretical model predicts cooperation throughout the race for the large prize and early cooperation giving way to competition for the small prize. The experimental evidence confirms this, although in a few races that started even the players never

42 However, unlike the other two cases in which the sample includes 19 races in each initial position, in the (0,2) initial position there are only 5 races for each value of the prize.

cooperated, while there was some cooperation during the race among uneven players. On a theoretical basis, we would expect no cooperation at all in this case. The empirical evidence from our tests nevertheless does, broadly speaking, confirm the theoretical indication that the incentive to cooperate is greater when players start out even than when one of the two has an initial advantage.

These conclusions were reached by making a number of simplifying assumptions. First, we assumed that the discount factor is arbitrarily small. If the firms had a high rate of time preference, we would expect them to play 2 at some stages in the cooperative regime as well. Also, we would expect less cooperation than in the case with no discount, because cooperation delays the innovation. On the other hand, a high degree of impatience may explain why some subjects in the experiment played the highest level of effort even in a situation of cooperation and why equally positioned players competed more than we predicted.

Second, we assumed there is no uncertainty in the R&D process, though firms do face uncertainty about the possibility of winning the race, due to imperfect information. We would expect this additional assumption to lead firms to increase cooperation in order to reduce uncertainty about success, though it should not change the results in qualitative terms.[43]

Third, although there are no spillovers in the model, the possibility of the loser's appropriating part of the benefits would increase competition in the ex post market. In the light of our previous results, we can infer that spillovers would reduce the incentive for joint discovery.

Finally, we assumed cost-reduction R&D. Quality improvement R&D would produce a greater incentive to innovate, because the conflict in the *ex post* market would not be as sharp, as firms could make a cooperative agreement to diversify their product quality choices.

Although the welfare evaluation of cooperation and competition in patent races is beyond the scope of this paper, the dynamic framework of the model captures some welfare effects of cooperation in R&D due to the timing of innovation. Cooperation in R&D is detrimental to consumers because it delays innovation but is beneficial to firms because it increases

43 This may occur when there is a high degree of uncertainty and the race is in the early stages, so that the trailer can leapfrog. On the other hand, if the race is near the end and the distance between the firms is great enough, uncertainty in the discovery process may not change the outcome, because firms are unlikely to make "big jumps".

profit. Therefore, welfare evaluation of R&D cooperation and competition in patent races must take account of the net effect on the consumers' and producers' surplus.

We would expect that if the value of the innovation is greater for consumers than firms, the best regime would be competition both in R&D and in the product market: the gains to consumers due to earlier innovation would outweigh the losses of firms from duplication of effort. On the other hand, if the value of the innovation were greater to firms than to consumers, collusion both in R&D and in the product market would be preferable.

Appendix 1

Proof of Proposition 1

Assume the players are in the same position and they split equally the prize (i.e., $k_i = k_j = 1$ and $\alpha_i^c = \alpha_j^c = 1/2$). In addition, let consider first the case $k \leq \bar{k}$.

The proof is by backward induction. So, assume firms are in the last period and there is one step to go.

First, notice that if firms break down the venture in the last period they will choose the highest level of effort: any other effort level by one firm would make the rival to win the race with certainty.

Therefore, in the last period firm $i, i = A, B$, undertakes an RJV iff $E\Pi_i^c(1,1) > E\Pi_i^{nc}(1,1)$, that is

$$\gamma V/2 - c_1/2 > V/2 - c_2. \tag{4}$$

Condition (4) above holds if

$$\gamma > \gamma' = \frac{V - c_2 - (c_2 - c_1)}{V}, \tag{4.1}$$

otherwise inequality (4) is reversed.

Next assume there are two steps to go. In this case the condition for cooperation are:

$$\gamma V/2 - c_1 > V/2 - c_2. \tag{5}$$

Condition (5) holds if

$$\gamma > \gamma'' = \frac{V - 2(c_2 - c_1)}{V}, \tag{5.1}$$

Comparing (4.1) and (5.1), it is straightforward to conclude that $\gamma' > \gamma''$.

If $k > 2$ the condition for cooperation becomes

$$\gamma > \gamma''' = \frac{V - k(c_2 - c_1)}{V}, \tag{6}$$

and (6) is weaker than conditions (5.1) and (6.1) above.

Finally, assume both firms are $k \geq \overline{k}$ steps from the finishing line,[44] and consider the incentive to cooperate when the value of the race is positive at the outset (i.e., $V - \overline{k}c_2 - jc_1 > 0, \quad j \geq 1$).

The conditions for firm $i, i = A, B$, to cooperate at the outset are:

$$\gamma > \hat{\gamma} = \frac{V - \overline{k}(c_2 - c_1) - jc_1}{V}, \tag{7}$$

and comparison of (6) and (7) shows that the condition for cooperation at the outset by even firms is weaker than in the subsequent periods of the race.

Notice that $\hat{\gamma}$ may be greater, lower or equal to $\tilde{\gamma}$. Hence, the following situations may result at the outset:

(a) $\hat{\gamma} > \tilde{\gamma}$ and the value of the race is positive (i.e., $V - \overline{k}c_2 - jc_1 > 0; j \geq 1$). In this case, firms undertake an RJV at the outset.

(b) $\hat{\gamma} \leq \tilde{\gamma}$ and the value of the race is positive. In this case, firms never cooperate in the patent race.

(c) $\hat{\gamma} > \tilde{\gamma}$ and the value of the race is negative (i.e., $V - \overline{k}c_2 - jc_1 > 0; j \geq 1$). In this case, an RJV not only is more feasible than in the case the value of the race is positive, but it may

44 Recall that for $k > \overline{k}$ firms cannot make all the periods the highest effort and get positive expected profits.

have the beneficial effect to induce the firms to undertake an otherwise excluded project.[45]

Proof of Proposition 2

Without loss of generality, assume firm A is the leader of the race, and consider the incentive to cooperate when firms are in the position (1, 2), and $\alpha_A^c = 1/2$. So firm A cooperates in the last period iff[46]

$$E\Pi_A^c(1,2) = \gamma V/2 - c_1/2 > E\Pi_A^{nc}(1,2) = V - c_2. \tag{8}$$

Notice that if (8) does not hold when $\gamma = 1$, a fortiori it does not hold for $\gamma < 1$. So, substituting $\gamma = 1$ into (8), after algebraic manipulation, the previous condition becomes:

$$V - c_1 > V - c_1 + V - c_2 - (c_2 - c_1) \tag{8a}$$

which never holds, since $V - (2c_2 - c_1) > 0$ by Assumption D1. So, we conclude that if $\alpha_A^c = 1/2$, the leader of the race does not cooperate in the last period when he is one step from the discovery and lags the follower by one step. Next, consider the incentive of the leader to cooperate in the previous periods.

When firms are in the position $(k, k+1), 2 < k \leq \overline{k}$, the condition for firm A to cooperate becomes:

$$V/2 - kc_1/2 > V - (k/2)c_2 \tag{9}$$

and it is easy to show that also the last inequality does not hold. Assume $k > \overline{k}$, and consider the incentive to cooperate when firms are in the position $(\overline{k}+1, \overline{k}+2)$. At this stage the leader cooperates iff

45 More precisely, in this case an RJV is undertaken if the saving on costs due to cooperation transforms a project with negative net value into one with positive net value.

46 Fudenberg et al. (1983) proved in the competitive case that the leader plays the mixed strategy [1,2]. It follows that by playing 2 with some positive probability it gets $V - c_2$, which is also the expected revenue that it would get by playing 1. The follower plays the mixed strategy [0,2], and get zero expected profit.

$$V/2 - (\overline{k}+1)c_1/2 > V - (\overline{k}/2)c_2 - c_1 \tag{10}$$

which never holds if the value of the race is positive. Finally, at the outset the last condition becomes

$$V/2 - (\overline{k}+j)c_1/2 > V - (\overline{k}/2)c_2 - jc_1 \tag{11}$$

that is

$$V - \overline{k}(c_2 - c_1) - jc_1 < 0 \tag{11a}$$

that never holds, provided that the value of the race at the outset is positive.

However, inequality (11a) shows that an RJV at the outset occurs among firms lagged by one step if the value of the race is negative and the R&D technology is sufficiently convex such that $\overline{k}(c_2 - c_1) > V - jc_1$. In this case, cooperation in R&D and the consequent cost reduction transforms an unprofitable project into one with positive expected profit.

Finally, notice that if the condition for cooperation holds at $\overline{k}+j$, both firms are in the same position in the next stages, and a fortiori they cooperate thereafter.

So far we considered the case $\gamma = 1$. For $\gamma < 1$, condition (11) becomes:

$$\gamma V/2 - (\overline{k}+j)c_1/2 > V - (\overline{k}/2)c_2 - jc_1 \tag{11b}$$

and by comparison of (11) and (11b), it is straightforward to conclude that it is less likely that the leader will cooperate in the case where firms cannot collude in the *ex post* market.

However, if the above conditions for cooperation hold, it follows that $\gamma > \overline{\gamma}$, where $\overline{\gamma}$ is the degree of competition in the *ex post* market which makes the leader indifferent between cooperating and competing in the race. In addition, by comparing (11b) and (7), it is straightforward to conclude that $\overline{\gamma} > \hat{\gamma}$, and from Proposition 1 we conclude that cooperation between uneven firms will last all through the race.

Finally, consider the case in which the leader is two steps ahead and there are $k, k = 1, \ldots, \overline{k}+j$ steps to go. Assume they collude in the product market. The condition for the leader to cooperate at $k, k = 1, \ldots, \overline{k}+j$, becomes

$$V/2 - kc_1/2 > V - kc_1 \tag{12}$$

which never holds, whatever the distance of the firms from the finishing line. A fortiori the leader does not cooperate when they compete in the *ex post* market.

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References

Anton, J. J., and Yao, A. (1994): "Expropriation and Inventions: Appropriable Rents in the Absence of Property Rights." *American Economic Review* 84 (1): 190–209.

Anton, J. J., and Yao, A. (2002): "The Sale of Ideas: Strategic Disclosure, Property Rights, and Incomplete Contracts." *Review of Economic Studies* 69(3): 513–531.

Bhattacharya, S., Glazer, J., and Sappington, D. E. M. (1992): "Licensing and the Sharing of Knowledge in Research Joint Ventures." *Journal of Economic Theory* 56: 43–69.

Brod, A., and Link, A. N. (1996): "On the Legal Environment of Research Joint Ventures." University of North Carolina at Greensboro. Working paper.

Caloghirou, Y., Ioannides, S., and Vonortas, N. S. (2003): "Research Joint Ventures." *Journal of Economic Surveys* 17: N. 4.

D'Aspremont, C., Bhattacharya, S., and Gérard-Varet, L. A. (1988): "Knowledge as a Public Good: Efficient Sharing and Incentives for Development Effort." *Journal of Mathematical Economics* 30(4): 389–404.

D'Aspremont, C., Bhattacharya, S., and Gérard-Varet, L. A. (2000): "Bargaining and Sharing Innovative Knowledge." *Review of Economic Studies* 67: 255–271.

De Fraja, G. (1990): "Strategic Disclosure of R&D Knowledge and Research Joint Ventures." University of Bristol, Department of Economics, Discussion paper no. 90/278.

De Fraja, G. (1993): "Strategic Spillovers in Patent Races." *International Journal of Industrial Organization* 11: 139–146.

Fershtman, C., and Kamien, M. I. (1992): "Cross Licensing of Complementary Technologies." *International Journal of Industrial Organization* 10: 329–348.

Fischbacher, U. (1999): *Zurich Toolbox for Readymade Economic Experiments.* Zurich.

Fudenberg, D., Gilbert, R., Stiglitz, J., and Tirole, J. (1983): "Preemption, Leapfrogging and Competition in Patent Races." *European Economic Review* 22: 3–31.

Grossman, G. M., and Shapiro, C. (1987): "Dynamic R&D Competition." *The Economic Journal* 97: 372–87.

Hagedoorn, J., Link, A. N., and Vonortas, N. S. (2000): "Research Partnerships." *Research Policy* 29: 567–586.

Harris, C., and Vickers, J. (1985): "Perfect Equilibrium in a Model of a Race." *Review of Economic Studies* 52: 193–209.

Harris, C., and Vickers, J. (1987): "Racing with Uncertainty." *Review of Economic Studies* 54: 1–22.

Hey, J. D., and Reynolds, M. L. (1992): "Experiments, Games and Economics." In *Artificial Intelligence and Economic Analysis: Prospects and Problems,* edited by S. Moss and J. Rae. Berlin: Edward Verlag.

Isaac, R. M., and Reynolds, S. S. (1988): "Appropriability and Market Structure in a Stochastic Invention Model." *Quarterly Journal of Economics* 103: 647–671.

Isaac, R. M., and Reynolds, S. S. (1992): "Schumpeterian Competition in Experimental Markets." *Journal of Economic Behaviour and Organization* 17: 59–100.

Judd, K. L. (1985): "Closed Loop Equilibrium in a Multistage Innovation Race." *Kellogg Graduate School of Management*. Discussion paper no. 647.

Kamien, I. M., Muller, E., and Zang, I. (1992): "Research Joint Ventures and R&D Cartels." *American Economic Review* 82: 1293–1306.

Katz, M. L., Ordover, J. A., (1990): "R&D cooperation and competition." In *Brookings Papers on Economic Activity, Microeconomics,* edited by M. N. Baily and C. Winston. Washington, DC: The Brookings Institution, pp. 137–91.

Perez Castrillo J. D., and Sandonís, J. (1996): "Disclosure of Know-how in Research Joint Ventures." *International Journal of Industrial Organization* 15: 51–75.

Reinganum, J. (1981): "Dynamic Games of Innovation." *Journal of Economic Theory* 125: 21–41.

Rosenkranz, S. (1997): "The 'Valentine's Day Problem': Cooperation under Two-sided Incomplete Information." Paper presented at the 24th E.A.R.I.E. Annual Conference, Leuven, Belgium, August 31–September 3, 1997.

Rosenkranz, S. (2001): "To Reveal or not to Reveal – Know-how Disclosure and Joint Ventures in Procurement Auctions." *Journal of Institutional and Theoretical Economics* 157(4): 555–567.

Roy Chowdhury, I., and Roy Chowdhury, P. (2001) "A Theory of Joint Venture Life-cycles." *International Journal of Industrial Organization* 19: 319–343.

Scott, J. T. (1993): *Purposive Diversification and Economic Performance*. New York: Cambridge University Press.

Scott, J. T. (1996): "Environmental Research Joint Ventures among Manufacturers." *Review of Industrial Organization* 11: 655–679.

Selten, R., and Stoecker, R. (1986): "End Behaviour in Sequences of Finite Prisoner's Dilemma Supergames: A Learning Theory Approach." *Journal of Economic Behaviour and Organization* 7: 47–70.
Silipo, D. B. (2000): "Cooperation and Competition in Patent Races: Theory and Experimental Evidence." Dipartimento di Economia e Statistica, Università della Calabria. Discussion paper no. 20.
Silipo, D. B., and Weiss, A. (2005): "Cooperation and Competition in an R&D Market with Spillovers". *Research in Economics* 59: 41–57.
Tao, Z., and Wu, C. (1997): "On the Organization of Cooperative Research and Development: Theory and Evidence". *International Journal of Industrial Organization* 15: 573–596.
Veugelers, R. (1993): *A Profile of Companies in Alliances.* Research Report D.T.E.W. 9325. Leuven: K. U. Leuven.
Veugelers, R., and Kesteloot, K. (1994): "On the Design of Stable Joint Ventures." *European Economic Review* 38: 1799–1815.
Veugelers, R., and Kesteloot, K. (1997): "Bargained Shares in Joint Ventures Among Asymmetric Partners: Is the Matthew Effect Catalyzing?" *Journal of Economics/Zeitschrift für Nationalökonomie* 64: 23–51.
Vonortas, N. S. (1997): "Research Joint Ventures in the US." *Research Policy* 26: 577–595.
Vonortas, N. S. (2000): "Multimarket Contact and Inter-firm Cooperation in R&D." *Journal of Evolutionary Economics* 10(1–2): 243–271.
Zizzo, D. J. (2002): "Racing with Uncertainty: a Patent Race Experiment." *International Journal of Industrial Organization* 20: 877–902.

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