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**DOES R&D COOPERATION FACILITATE  
PRICE COLLUSION? AN EXPERIMENT**

By S. Suetens

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# Does R&D cooperation facilitate price collusion? An experiment.

**Sigrid Suetens** \*

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## **Abstract**

In the paper the impact of R&D cooperation on prices in experimental duopoly markets is examined. As a theoretical benchmark for the experiment, a two-stage duopoly model with an R&D stage with technological spillovers and a pricing stage is used. For two scenarios of technological spillovers (no versus complete spillovers), a treatment where it is possible to credibly commit to an R&D contract and a baseline treatment without binding contract possibilities, are run. Findings are that, in general, prices are between the subgame perfect Nash and the cooperative level. Further, for both spillover levels prices are higher in periods where R&D contracts are committed to, than in other periods, and to a lesser extent compared to the baseline treatments.

**JEL codes:** C90, L13, O31.

**Keywords:** R&D, duopoly, experiment, price collusion.

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\*University of Antwerp, Faculty of Applied Economics, Prinsstraat 13, 2000 Antwerp, tel: +32 3 220 40 38, e-mail: sigrid.suetens@ua.ac.be. The experiment in this paper has been run during my Marie Curie stay at CentER (University of Tilburg) from February to June 2003. I thank Jan Potters, Chun-Lei Yang and participants of the 2003 ESA conference in Pittsburgh for providing me useful comments. The University of Tilburg is gratefully acknowledged for financial support.

# 1 Introduction

To protect consumers, European and American antitrust laws forbid firms to engage in price collusion or in other explicit or implicit agreements that restrict output and harm consumers. At the same time the formation of research joint ventures or agreements that are related to cooperation in R&D are not forbidden but rather encouraged by European and American governments because of their welfare-enhancing effects. A large strand of theoretical literature based on the seminal paper of d'Aspremont and Jacquemin (1988) has dealt with the comparison of outcomes of non-cooperative oligopoly R&D games with cooperative R&D outcomes with possible technological spillovers in a first stage and usually competition in the output stage. Examples are Kamien et al. (1992); Leahy and Neary (1997); Petit and Tolwinski (1999); Hinloopen (2000). The models are of a non-tournament kind. The main finding is that if the spillover parameter lies above a threshold value, welfare is higher when firms cooperate in R&D compared to when they compete in R&D, while it is the other way around for a spillover below the threshold value. This result provides a rationale for governments to stimulate horizontal R&D cooperation in industries with large technological spillovers. The finding is based on the assumption that firms engage either in Cournot or Bertrand competition in the output market. An important question that has mostly been neglected in this stream of literature is whether cooperation in the R&D stage facilitates collusion in the output stage.

There have been some attempts in the theoretical literature to establish a link between cooperation in the R&D stage and cooperation in the output stage, though usually the frameworks that are used for this purpose are somewhat different from the one in the above mentioned strand of literature. In Martin (1995) the effects of R&D joint ventures on the pervasiveness of tacit collusion in the product market are examined in a patent race model without technological spillovers. The author uses a non-cooperative game-theoretic framework and assumes that firms follow a trigger strategy with product market collusion being an equilibrium strategy when the present value of profits gained from colluding is larger than the present value of profits gained from defecting. It is found that voluntarily forming an R&D joint venture makes it more likely for tacit collusion to be sustained in the product market. In Cabral (2000) interactions between R&D and price decisions are examined in an infinite duopoly framework where firms are to make R&D and price decisions simultaneously. Only if R&D is successful, higher profits are gained. The findings are that self-enforcing R&D agreements that increase R&D towards an efficient level decrease prices while R&D contracting results in increased prices. Lambertini et al. (2002) examine the interplay between

product R&D and pricing decisions in a non-cooperative framework and find that independent ventures that lead to horizontal product differentiation can facilitate price collusion. Finally, van Wegberg (1995) is based on an extension of d'Aspremont and Jacquemin (1988) to a model with three firms and products that are imperfect substitutes. In the paper some specific cases are identified in which the formation of an R&D alliance of two out of three firms could lead to collusion in output in an infinitely repeated non-cooperative game context. I am not aware of any empirical papers that deal with the topic.

Examples of laboratory experiments where subjects were to make R&D and price/quantity decisions are Isaac and Reynolds (1992) and Jullien and Ruffieux (2001). The former builds on a stochastic invention model of innovation, where the probability of producing a practically relevant innovation depends on the amount of R&D investment of a firm. The experimental results give support to behavior that the authors classify as Schumpeterian competition, which is characterised by a combination of engagement in costly innovation and falling prices and by rising concentration. Oligopoly R&D investment is generally lower than the social optimum, except in the last periods, but it is unclear whether it is close to an equilibrium prediction. In the experiments of Jullien and Ruffieux (2001), firms could either adopt an existing technology, that would reduce production costs in a known way, or develop a new technology, with an uncertain outcome. They introduce spillovers by letting R&D decisions of a firm yield industry-wide cost reductions with a time lag. It is found that market prices generally converge towards their competitive level and that markets thus are efficient. When all oligopolists simultaneously gain a cost reduction that shifts the aggregate supply curve downwards, adjustment of market prices to their new competitive level is slower and benefits of the innovations initially solely accrue to producers. Uncertainty yields prices that are further away from equilibrium predictions and only R&D decisions with uncertainty are reduced by spillovers.

Another set of R&D experiments is found in Suetens (2003a) and Suetens (2003b), where the former includes a binding contract treatment and the latter a non-binding communication treatment. In both papers, a two-stage duopoly framework is used and it is assumed that in the second stage, firms are engaged in Cournot competition. As such, only R&D decisions, and not quantity or price decisions are investigated. Findings are that either without or with full technological spillovers, contracted R&D converges to the cooperative level and R&D in the fully competitive game converges to the subgame perfect Nash level. Non-binding communication leads to the cooperative R&D level, only if technological spillovers are complete.

In this paper an experiment is set up to examine whether in a non-tournament duopoly framework with two stages, i.e. an R&D stage and a pricing stage, R&D cooperation enhances price collusion. This approach is novel in the sense that the relation between cooperation in the R&D stage and cooperation in the output stage has not been examined in an experiment before. Furthermore, we are not aware of any experimental papers on R&D and pricing behavior that allow firms to sign R&D contracts. In part of the treatments subjects have the possibility to make binding R&D agreements in the first stage and the rest of the treatments are simply baseline treatments without any contract possibilities. Given the importance of the level of technological spillovers in non-cooperative and cooperative R&D literature and the differences in R&D behavior in a non-cooperative context found in Suetens (2003b), a distinction is also made between a scenario without spillovers and a scenario with full spillovers. The remainder of the paper is organized as follows. In section 2 an overview is given of the theoretical predictions of the non-cooperative and cooperative duopoly models. Section 3 describes the experimental design and procedure that has been followed. Sections 4 and 5 analyze the experimental R&D decisions and prices respectively and section 6 concludes.

## 2 Theoretical predictions

The model that serves as a benchmark for the experiment is based on Kamien et al. (1992) and d'Aspremont and Jacquemin (1988)<sup>1</sup>. In the model two firms in duopoly sell differentiated products and face a linear inverse demand curve of  $p_i(q_i, q_j) = a - bq_i - cq_j$ , with  $i, j = 1, 2$  and  $i \neq j$ <sup>2</sup>. The firms decide on R&D investment in a first stage and make price decisions in a second stage. Investing in R&D reduces unit production cost and has decreasing returns<sup>3</sup>. It is further assumed that technological spillovers arise, such that effective R&D investment of a firm consists of its own R&D investment and a part of the R&D of the competitor that has spilled over. Replacing quantities by the direct demand curves yields the following profit function of firm  $i$  for  $i = 1, 2$

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<sup>1</sup>Henceforth KMZ and AJ.

<sup>2</sup>The utility function that results in this set of demand curves for firms  $i$  and  $j$  has a standard quadratic form. It is represented by  $U(q_1, q_2) = a(q_1 + q_2) - \frac{b}{2}(q_1^2 + q_2^2) - cq_1q_2$  (Singh and Vives, 1984; Hinloopen, 2000).

<sup>3</sup>For large spillovers, returns to effective R&D are increasing in the original AJ model, but by using an alternative specification for the R&D cost function, this is avoided. See Amir (2000) for a thorough comparison between AJ and KMZ.

and  $j \neq i$ :

$$\pi_i = \left( \frac{a}{b+c} - \frac{bp_i - cp_j}{b^2 - c^2} \right) (p_i - [\alpha - (x_i + \beta x_j)]) - \delta \frac{x_i^2}{2}. \quad (1)$$

where  $p_i$  is the price of products of firm  $i$  and  $x_i$  the R&D investment of firm  $i$ .  $\beta$  represents the spillover parameter that lies between 0 and 1,  $\alpha$  stands for unit production cost if no R&D is done by neither of the firms and the last term of the profit function is the R&D cost function. As to obtain decreasing returns to *effective* R&D and as such, equivalence between results of the AJ and KMZ models, the suggestion of Amir (2000) to use a steeper R&D cost function has been taken into account. In the R&D cost function,  $\delta = \gamma(1 + \beta)$  where  $\gamma$  is the original AJ cost parameter. By using this alternative cost function, equilibrium R&D predictions are those of KMZ and decision variables in the first stage of the game are unit cost reductions as in AJ<sup>4</sup>. The two-stage game is solved by backward induction. Since firms are not allowed to make binding agreements in the product market, the solution concept of the second stage of the game is subgame perfect Nash equilibrium. Thus, profit of firm  $i$  with  $i = 1, 2$  is maximized with respect to its price. This yields an equilibrium solution for the price of  $i$ , in terms of the R&D decisions of both firms, of

$$p_i = \frac{(2b+c)[a(b-c) + \alpha b] - b[(2b+\beta c)x_i + (2b\beta+c)x_j]}{4b^2 - c^2}. \quad (2)$$

If firms do not have the possibility to make binding agreements with respect to their R&D investment in the R&D stage, this stage is also played non-cooperatively. The solution concept is again subgame perfect Nash equilibrium. Filling in the equilibrium prices (equation 2) in the profit function (equation 1) and maximizing the first-stage profit function for both firms with respect to R&D yields the following (symmetric) R&D equilibrium<sup>5</sup>:

$$x^* = \frac{2b(a-\alpha)(2b^2 - b\beta c - c^2)}{(1+\beta)[\gamma(b+c)(2b+c)(2b-c)^2 - 2b(2b^2 - b\beta c - c^2)]}. \quad (3)$$

If firms are allowed to make binding R&D agreements and can reliably commit to a cooperative R&D level, joint profit is maximized with respect to

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<sup>4</sup>In Amir (2000) this is proven for the case of quantity competition with homogenous products, but it can be shown that the same conclusions are valid for price competition with differentiated products.

<sup>5</sup>It is assumed that the second-order conditions and the stability conditions suggested by Henriques (1990) are met.

R&D. Restricting the solution to be symmetric yields the following unique cooperative outcome<sup>6</sup>:

$$x^{**} = \frac{2b(a - \alpha)(b - c)}{\gamma(b + c)(2b - c)^2 - 2b(1 + \beta)(b - c)}. \quad (4)$$

The cooperative R&D level is larger (smaller) than the competitive R&D level if actions in the R&D stage are strategic complements (substitutes), i.e. if  $\beta > (<) \frac{bc}{2b^2 - c^2}$ . Profit that corresponds to R&D cooperation is higher than profit under R&D competition if  $\beta \neq \frac{bc}{2b^2 - c^2}$ .

Finally, another benchmark case is looked at, i.e. price collusion. If the firms collude in prices, such that joint profit is maximized, the following price comes out for firm  $i$  with  $i, j = 1, 2$  and  $i \neq j$  in terms of own R&D and R&D of the other firm:

$$p_i = \frac{a + \alpha - (x_i + \beta x_j)}{2}. \quad (5)$$

Obviously, given the R&D decisions, the collusive price is higher than the Nash level for all parameter values. If firms expect to collude in the second stage, their profit to be maximized in the first stage is formulated in terms of the collusive prices. This yields other predictions for the competitive and cooperative R&D levels. These are respectively

$$x^* = \frac{(a - \alpha)[2b - c(1 + \beta)]}{(1 + \beta)[4\gamma(b - c)(b + c) - 2b(2b - c(1 + \beta))]}, \quad (6)$$

$$x^{**} = \frac{(a - \alpha)}{2\gamma(b + c) - (1 + \beta)}. \quad (7)$$

Based on the predictions of the model, the hypotheses to be tested experimentally are formulated. The main hypothesis is the following.

**Hypothesis 1** *Prices are at their subgame perfect Nash level, irrespective of whether binding R&D agreements can be made.*

Other theoretical predictions regarding R&D decisions are summarized in the following hypotheses.

**Hypothesis 2** *If binding R&D agreements cannot be made, R&D investment is at its competitive level.*

**Hypothesis 3** *If binding R&D agreements can be and are made, R&D investment is at its cooperative level.*

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<sup>6</sup>It is again assumed that second-order and stability conditions are met. Another assumption is that the condition suggested by Salant and Shaffer (1998) is met such that the cooperative R&D level is unique and symmetric.

### 3 Experimental procedure

The experiment was run at Tilburg University and consisted of six computerized sessions with a total number of 114 recruited students<sup>7</sup>. Most students were undergraduate economics students and participated before in other experiments, but not in this kind of experiment. Each session lasted for two hours and earnings were between 7 and 30 EUR. Before the experiment started, instructions were handed out and the students had the opportunity to ask questions in private. Treatments with and without a possibility to engage in a binding R&D agreement (contract) with the other producer of the same duopoly have been implemented for industries without technological spillovers and industries with complete technological spillovers. As such, the experiment consisted of four treatments, i.e. a treatment without contract possibilities and a treatment with contract possibilities, both for  $\beta = 0$  and  $\beta = 1$  (henceforth  $T_{00}$ ,  $T_{10}$ ,  $T_{01}$  and  $T_{11}$ , where the first dummy in the index refers to the degree of spillover and the second to the contract possibility). The number of students that participated in the treatments are 30 in  $T_{00}$ , 22 in  $T_{10}$ , 32 in  $T_{01}$  and 30 in  $T_{11}$ , which corresponds to a total of 57 duopolies of which 15 are in  $T_{00}$ , 11 in  $T_{10}$ , 16 in  $T_{01}$  and 15 in  $T_{11}$ .

With respect to the choice of parameter values, we have tried to ensure that the profit increases that correspond to a price increase and a change in R&D decision are ‘high enough’. But it is inherent to the model that the relative change in profit that results from a price change is much higher than the profit change that results from a change in R&D decision. Parameter values that were used in the experiment are  $a = 245$ ,  $\alpha = 50$ ,  $b = 5$ ,  $c = 3.35$  and  $\gamma = 0.96$ . Corresponding theoretical predictions and benchmarks are in table 1. Turning from the individual profit maximizing R&D level to the joint profit maximizing level yields a profit increase of 3 to 9%, depending on pricing behavior and the level of spillovers, while turning from the individual to the joint profit maximizing price yields a profit increase of 29 to 39%, depending on R&D behavior and the level of spillovers.

The instructions made clear that the subjects represented a seller/producer of an unspecified product in a market with two sellers of a similar product and that demand of consumers was simulated by the computer. They were told that consumers buy more (less) of their product and less (more) of the product of the other producer, the lower (higher) the prices of their product. In all markets the simulated inverse demand curve was  $p_i(q_i, q_j) = 245 - 5q_i - 3.35q_j$  yielding a demand curve of  $q_i(p_i, p_j) \approx 29.34 - 0.36p_i + 0.24p_j$ . The subjects knew that the other seller in their market was subject to the same condi-

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<sup>7</sup>The software *z-Tree*, developed by Fischbacher (1999), has been used.



	$x^*$	$x^{**}$	$X^*$	$X^{**}$	$p^*$	$p^{**}$	$\pi^*$	$\pi^{**}$
Price competition								
$\beta = 0$	17.4	9.5	34.8	19.0	85.3	91.2	862.6	891.0
$\beta = 1$	4.8	10.0	9.6	20.0	91.2	83.3	913.8	936.8
Price collusion								
$\beta = 0$	28.0	13.0	56.0	26.0	133.5	141.0	1112.1	1214.2
$\beta = 1$	6.5	13.9	13.0	27.8	141.0	133.6	1254.6	1300.7

Table 1: Theoretical benchmarks

tions. They were asked to make investment and price decisions in a first and second stage respectively, during 40 rounds, of which the first 5 served as practice rounds and were ignored when calculating final remunerations. Investment had to be between 0.0 and 50.0 and the price between 0.0 and 245.0. Once an investment decision was made, it remained the same for five periods, which implies that investment decisions only had to be made every five periods. In this way, subjects could better learn to make price decisions. Price decisions had to be made in all 40 periods. When all investment decisions were entered, subjects were informed about their own and the decision of the other duopolist and the following stage started. When all price decisions were entered, they were informed about the price decisions made in that period and about (experimental) profit of both. Remunerations were calculated by dividing the sum of all earned profits during 35 rounds by 1500. The subjects were told that after the practice rounds they were re-matched with a different partner that was fixed for the rest of the rounds, while actually they kept the same partner. Subjects had no knowledge of the identity of their counterparts.

Subjects were explained that the investment reduced the cost of producing one unit of their product by the amount of the investment (and of the unit production cost of the other producer in the same duopoly in the treatments with complete spillovers) on the one hand and that it introduced a cost of half of the square of the amount (the square of the amount in the complete spillovers treatments)<sup>8</sup> on the other hand. A profit calculator was always available where own profit and profit of the other duopolist could be automatically calculated if fictive values of investment and price decisions were filled in. All decisions of the previous period were also shown on the screen. In the contract treatments an additional frame was shown on the screen in which subjects could send a symmetric contract proposal to the other player. The contract was binding in that once a contract was accepted,

<sup>8</sup>The parameter value of  $\gamma$  has been set to 0.96, such that  $\delta \approx 1$  when no spillovers are present and  $\delta \approx 2$  for complete spillovers.

both parties could not make another investment decision than the one agreed on in the contract. It was stressed that once a proposal was sent, the sender was committed to the proposal if the other player accepted the proposal, even if other proposals were made. All contract proposals were numbered and if a contract was accepted, the number of the accepted contract was shown on the screen.

## 4 Prices

The analysis of the experimental data is split up in two parts. In this section we look at price decisions and R&D decisions are dealt with in the next section. Price decisions are considered first, since it is necessary to have information on pricing behavior to be able to make conclusions regarding R&D behavior. As decisions of a subject are not independent of decisions of his/her counterpart, averages of price decisions and sums of R&D decisions by duopoly are used in the data analysis. In the first subsection a descriptive and a more conservative statistical analysis are concentrated on. The second subsection contains an econometric analysis aimed at calculating long-term equilibrium values of prices. Based on these long-term equilibrium prices, conclusions regarding R&D decisions can be made.

### 4.1 Descriptive and statistical analysis

Averages of prices over all periods and over the last ten periods are in table 2<sup>9</sup>. Within the contract treatment, a further distinction is made on the basis of whether a contract has actually been chosen or not, which is represented by a third index. Averages of prices in periods in which R&D contracts have been committed to, are referred to as 0 in the third subscript and averages of prices in periods without R&D contracts are referred to as 1. It is observed that without spillovers, prices in the treatment with contract possibilities are higher than prices in the treatment without contract possibilities. Further, within the treatment without technological spillovers and with contract possibilities, prices in periods in which R&D contracts are actually committed to are higher than in periods without R&D contracts. Prices with technological spillovers are not that different between the treatments without and with contract possibilities and within the contract treatment, between contract and no-contract periods.

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<sup>9</sup>In 14 out of 1995 (57\*35) cases, prices were chosen that yielded a negative production quantity. These observations were left out of the descriptives tables and the data analysis and had no effect on any of the conclusions made.

	$\bar{p}_{1-35}$	$\bar{p}_{26-35}$
$\beta = 0$		
$T_{00}$	94.5 (18.9)	99.5 (23.5)
$T_{01}$	103.1 (19.1)	106.5 (22.4)
$T_{010}$	88.8 (10.7)	87.2 (8.6)
$T_{011}$	111.0 (18.4)	114.9 (22.0)
$\beta = 1$		
$T_{10}$	93.5 (16.0)	96.6 (14.3)
$T_{11}$	93.4 (18.7)	96.1 (19.6)
$T_{110}$	86.9 (18.4)	85.5 (7.9)
$T_{111}$	93.3 (19.4)	93.1 (23.3)

Table 2: Average prices and standard deviations

Note that for  $\beta = 1$  the average price in the contract treatment in periods without R&D contracts is 85.5 and is 93.1 in periods with contracts and the average price in the last ten periods of the contract treatment is 96.1, while we would expect it to be somewhere between 85.5 and 93.1. This observation can be explained by a combination of the following facts. First, prices of subjects that always choose to commit to an R&D contract are quite high. Second, prices of subjects that switch between committing and not committing to a contract are generally higher when contracts are not committed to—but not as high as prices of subjects that always commit—than when they are committed to.

Having made their R&D decisions, the possibility exists that in the pricing stage subjects get locked in local optima, since theoretical Nash and collusive prices are expressed in terms of own and other firm’s R&D. It would thus be misleading to compare prices in the experiment with the benchmark prices presented in table 1 without taking into account the actual R&D decisions. Instead, the experimental price in a certain period should be compared with the benchmarks in equations 2 and 5, calculated on the basis of the R&D decisions made in that period. As a consequence, for each combination of R&D decisions, a separate set of Nash and collusive prices should be calculated. Further, to avoid the inconvenience of having two different benchmarks, i.e. a Nash and a collusive price, experimental prices are transformed taking into account Nash and collusive prices based on the experimental R&D decisions into the following variable:

$$P_{kt} = \frac{\bar{p}_{kt} - \bar{p}_{kt}^{Nash}}{\bar{p}_{kt}^{Collude} - \bar{p}_{kt}^{Nash}}. \quad (8)$$

the bar refers to averages of individual prices within duopoly  $k$ ,  $t$  to the period and indices *Nash* and *Collude* refer to the Nash price prediction

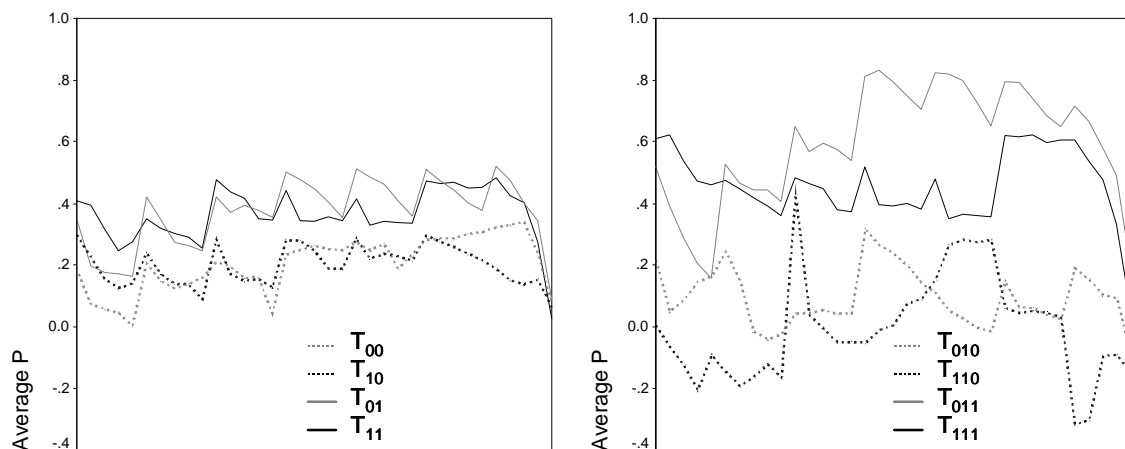


Figure 1: Evolution of average  $P$

based on equation 2 and the collusive price based on equation 5 respectively.  $P_{kt}$  measures the extent to which the average price of duopoly  $k$  in period  $t$  is closer to its Nash or cooperative level. If the price is at the Nash level,  $P_{kt}$  is equal to 0 and if the price is at the cooperative level,  $P_{kt}$  is equal to 1. For a price situated between the Nash and the cooperative level,  $P_{kt}$  is between 0 and 1. The transformed variable has the additional advantage that price decisions become comparable across spillover levels.

The evolution of average transformed prices is in figure 1 and averages and standard deviations of the transformed prices are in table 3. Note that for convenience, we simply apply the notation  $P$  to indicate transformed prices. Within the contract treatment, a further distinction is again made on the basis of whether a contract has actually been chosen or not, which is again represented by a third index. Thus, the left graph of the figure represents average prices of each treatment and the right graph represents averages of prices within the contract treatments, where a distinction is made between periods with and without R&D contracts.

In the table and the figure it is observed that mostly,  $P$  is between 0 and 1 which implies that prices usually are above the Nash level and below the cooperative level. Only in periods without R&D contracts in the contract treatments, prices seem to be quite close to the Nash level. Further, standard deviations are quite high, which indicates that large differences exist in individual pricing strategies. The most important observations are that, for both spillover levels, average transformed prices in the contract treatments are above prices in the baseline treatments. And within the contract treat-

	$P_{1-35}$	$P_{1-10}$	$P_{11-25}$	$P_{26-35}$
$\beta = 0$				
$T_{00}$	0.21 (0.33)	0.11 (0.27)	0.22 (0.40)	0.28 (0.41)
$T_{01}$	0.37 (0.32)	0.25 (0.25)	0.42 (0.39)	0.40 (0.39)
$T_{010}$	0.12 (0.19)	0.12 (0.19)	0.19 (0.31)	0.06 (0.14)
$T_{011}$	0.49 (0.33)	0.39 (0.24)	0.63 (0.34)	0.56 (0.37)
$\beta = 1$				
$T_{10}$	0.20 (0.30)	0.17 (0.30)	0.22 (0.33)	0.20 (0.31)
$T_{11}$	0.36 (0.32)	0.32 (0.38)	0.37 (0.37)	0.39 (0.35)
$T_{110}$	0.07 (0.34)	-0.09 (0.12)	0.18 (0.37)	-0.03 (0.18)
$T_{111}$	0.41 (0.29)	0.45 (0.30)	0.40 (0.36)	0.43 (0.31)

Table 3: Average  $P$  and standard deviations

ments, transformed prices in periods in which contracts are committed to, are above prices in no-contract periods. Another observation is that average transformed prices often increase during the experiment and decline again at the end of the experiment, which could be due to an end effect. From figure 1 it becomes clear that also within each five periods with a constant R&D decision, prices usually decline towards the final of the five periods.

Further, we test whether differences in (transformed) prices between treatments and within the contract treatments are statistically significant. Results of non-parametric tests are in table 4. The table should be interpreted as follows. Results of Mann-Whitney tests of differences between the treatments without and with contract possibilities are under the header ‘Between’ and results of Wilcoxon signed ranks tests of differences within the contract treatments between prices in contract and no-contract periods are under ‘Within’. General results —i.e. results without distinguishing between the two levels of technological spillovers— are presented, as well as separate results for both spillover levels. The presentation of the general results is justified, since non-parametric tests (of which the statistics are not presented here) do not find significant differences in prices between  $\beta = 0$  and  $\beta = 1$ . Consider first the general results without distinguishing between the two spillover levels. The Mann-Whitney statistics indicate that a significant difference in transformed prices exists between the treatments without and with contract possibilities, either with a 5% significance level for all and the first ten periods or with a 10% significance level for the middle 15 and the last ten periods. More specifically, prices in contract treatments are higher than prices in treatments without contract possibilities. The statistical significance is quite marginal, which is further illustrated by the results of the between-tests for the separate spillover levels. Indeed, when considering the results for each spillover

	Between			Within		
	all	$\beta = 0$	$\beta = 1$	all	$\beta = 0$	$\beta = 1$
<i>All periods</i>						
<i>z</i>	-2.083	-1.502	-1.427	-3.841	-2.756	-2.701
exact sig. (2-tailed)	0.037	0.140	0.164	0.000	0.006	0.007
N	57	31	26	21	11	10
<i>Periods 1-10</i>						
<i>z</i>	-2.067	-1.660	-1.116	-2.366	-2.023	-1.342
exact sig. (2-tailed)	0.039	0.101	0.264	0.018	0.043	0.180
N	57	31	26	7	5	2
<i>Periods 11-25</i>						
<i>z</i>	-1.698	-1.304	-0.960	-2.599	-1.095	-2.201
exact sig. (2-tailed)	0.089	0.202	0.357	0.009	0.273	0.028
N	57	31	26	11	4	7
<i>Periods 26-35</i>						
<i>z</i>	-1.794	-1.186	-1.479	-2.547	-1.604	-1.992
exact sig. (2-tailed)	0.073	0.247	0.148	0.011	0.109	0.046
N	57	31	26	9	3	6

Table 4: Mann-Whitney and Wilcoxon signed ranks test results for prices

level separately, the significance disappears if 2-tailed tests with a significance level of 5% are relied on.

Further, from the table it becomes clear that taking into account whether contracts have actually been committed to, within the contract treatments, is important. Indeed prices in periods with R&D contracts are generally found to be significantly higher than prices in periods without contracts, for the whole period and for all sub-periods. When considering the spillover levels separately, the significance in some of the sub-periods decreases, probably because there are too few observations in these sub-periods. E.g. for  $\beta = 0$  only 3 observations underlay the Wilcoxon test in the last sub-period, implying that 3 out of 16 duopolies switched between choosing and not choosing an R&D contract in the last sub-period.

To summarize, if no distinction is made between treatments with and without technological spillovers such that all observations of the contract treatments on the one hand and the treatments without contract possibilities on the other hand, are taken together, transformed prices in the contract treatments are found to be higher than prices in the treatments without contract possibilities, with a statistical significance level of 5%. Beside this, even stronger statistical evidence is found for a within-difference in the contract treatments. I.e. prices in periods in which R&D contracts are actually committed to, are higher than prices in periods without R&D contracts.

## 4.2 Econometric analysis

As to make final conclusions on the hypotheses regarding pricing and R&D behavior, general transformed price levels (i.e.  $P$ ) that are representative for each treatment and within the contract treatment, for periods with and without R&D contracts, should be found. We could use simple averages to represent the general transformed prices, but then we would have to make arbitrary choices on the periods to base the calculations on. Should all periods be taken into account then, or only e.g. the last ten periods? Besides, in the previous subsection it became clear that for some sub-periods, too few observations were available to calculate averages that are representative for price decisions (cfr. few duopolies switch between contracting and not contracting in certain sub-periods). Another disadvantage of this approach is that the dynamics and the time series character of the experimental data are ignored. When using econometrics to calculate the long-term prices, these problems are avoided (see also Königstein, 2000).

It is assumed that the price decision of each duopoly and in each period is equal to the sum of a constant term and a duopoly- and time-specific residual fluctuation that follows an autoregressive process of order 2. Dummies that represent the spillover parameter, the treatment and the use of R&D contracts are also included. As such, the long-run transformed prices of each treatment are estimated, based on the following econometric equations<sup>10</sup>,

$$P_{k,t} = \lambda_0 + \lambda_1\beta_k + \lambda_2CON_k + \lambda_3COMM_{k,t} + u_{k,t} \quad (9)$$

$$u_{k,t} = \rho_1u_{k,t-1} + \rho_2u_{k,t-2} + \epsilon_{k,t}. \quad (10)$$

$\beta_k$  represents the spillover parameter of duopoly  $k$ ,  $CON_k$  is a dummy that is 1 when duopoly  $k$  had contract possibilities (contract treatment) and 0 otherwise and  $COMM_{kt}$  is equal to 1 when within a contract treatment duopoly  $k$  has committed to an R&D contract in period  $t$  and 0 otherwise.  $\epsilon_{k,t}$  follows a white noise process. A parameter of  $CON_k$  that is statistically different from zero, implies that transformed prices differ in a statistically significant way between treatments without and with contract possibilities. When the parameter of  $COMM_{kt}$  is statistically different from zero, the transformed price that is representative for the no-contract treatments and for periods without R&D contracts in the contract treatments, differs in a statistically significant way from the price in periods with contracts. Similarly, when the parameter of  $\beta_k$  is statistically significant, a difference in transformed prices between the two spillover levels exists.

<sup>10</sup>The residual AR(2) process is stationary and converges if  $|\rho_1| < 1$ ,  $|\rho_2| < 1$ ,  $\rho_1 + \rho_2 < 1$  and  $\rho_2 - \rho_1 < 1$  (Greene, 2000).

	parameter estimates (p-values)		
	(1)	(2)	(3)
1	0.227 (0.000)	0.227 (0.000)	0.180 (0.000)
$\beta_k$	-0.104 (0.200)	-0.104 (0.199)	-
$CON_k$	-0.001 (0.993)	-	-
$COMM_{k,t}$	0.170 (0.000)	0.170 (0.000)	0.168 (0.000)
$u_{k,t-1}$	0.809 (0.000)	0.809 (0.000)	0.810 (0.000)
$u_{k,t-2}$	0.093 (0.000)	0.093 (0.000)	0.093 (0.000)
$R^2$	0.819	0.819	0.819
$DW$	1.922	1.922	1.921

Table 5: Econometric estimates

Results of pooled feasible GLS estimation of equations 9 and 10 are in table 5. Estimates of the equations with all variables included, are in column (1), estimates without the inclusion of  $CON_k$  because of its insignificance are in (2), and estimates without  $CON_k$  and  $\beta_k$  are in (3). P-values of t-tests with the null hypothesis that the parameter of the corresponding variable is zero are in brackets. From column (1) in the table we learn that the constant term,  $COMM_{kt}$  and the autoregressive terms are highly significant. The statistical insignificance of  $CON_k$  implies that prices in the treatments without contract possibilities are not different from prices in periods without R&D contracts in the contract treatments. In the following estimations, the variables that are found to be insignificant in the first estimation are gradually left out. In the second estimation,  $CON_k$  is left out and in the third estimation also  $\beta_k$  is left out. Note that the parameter estimate that corresponds to the spillover parameter has a negative sign, which implies that transformed prices in the treatments with spillovers, are lower than transformed prices in the treatments without spillovers. But since it is also found to be not significant, we do not pay any further attention to this.

Looking at the results of the final estimation in column (3), we observe that the constant term is 0.18 and highly significant. This constant term represents the (general) long-run transformed price in the treatments without R&D contract possibilities and in the contract treatments in periods where no R&D contracts were actually committed to. Thus, prices generally are above the Nash level. The estimate of the parameter of the dummy that is one in periods where an R&D contract has been committed to ( $COMM_{kt}$ ) is positive, which indicates that transformed prices are significantly higher in periods in which contracts have been committed to, than in periods without R&D contracts (in the contract and no-contract treatments). The long-run transformed prices based on these estimations are in table 6 and are presented



$T$	(1)	(2)	(3)
$T_{00}$	[ 0.09 , 0.36 ]	[ 0.12 , 0.33 ] <sup>a</sup>	[ 0.10 , 0.26 ] <sup>c</sup>
$T_{010}$	[ 0.09 , 0.36 ]	-	-
$T_{011}$	[ 0.26 , 0.53 ]	[ 0.29 , 0.51 ]	[ 0.25 , 0.44 ] <sup>d</sup>
$T_{10}$	[ -0.02 , 0.27 ]	[ 0.00 , 0.24 ] <sup>b</sup>	-
$T_{110}$	[ -0.02 , 0.26 ]	-	-
$T_{111}$	[ 0.16 , 0.43 ]	[ 0.17 , 0.41 ]	-

<sup>a</sup>Includes  $T_{010}$ .  
<sup>b</sup>Includes  $T_{110}$ .  
<sup>c</sup>Includes  $T_{010}$ ,  $T_{10}$  and  $T_{110}$ .  
<sup>d</sup>Includes  $T_{111}$ .

Table 6: 95% confidence intervals of long-run transformed prices

in the form of 95% confidence intervals. Thus with a 95% probability the true long-run transformed prices will be in the intervals that are given in the table.

First, it is confirmed in table 6 that transformed prices significantly differ from zero and one in most cases, implying that prices are mostly not at the individual profit maximizing, nor at the joint profit maximizing level. Thus, hypothesis 1 is generally rejected by the experimental data. In general, conclusions on the comparison of (transformed) prices between treatments without and with contract possibilities, and within the contract treatments, between prices in periods without and with R&D contracts, are the same for both levels of technological spillovers. Besides, we already found that no significant difference exists between prices with complete spillovers and prices without spillovers. Transformed prices that are representative for treatments without contract possibilities and for periods without R&D contracts in treatments with contract possibilities, and for both spillover levels, are between 0.10 and 0.26, as can be read from table 6. Transformed prices in periods with R&D contracts in the contract treatments generally are between 0.25 and 0.44, and thus significantly higher. To conclude this section, there exists strong evidence that committing to R&D contracts increases prices in industries without and with full technological spillovers.

## 5 R&D decisions

In this section we focus on R&D behavior in the experiment. To get a first idea of the distribution of the experimental R&D decisions and the possible presence of outliers in the data, we refer to the box plots in figure

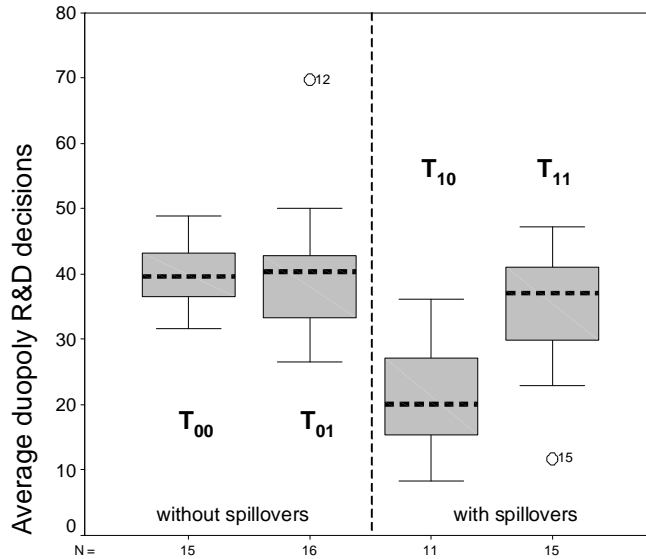


Figure 2: Boxplot of R&D decisions

2. The boxes represent the inter quartile range of the data and the whiskers represent the highest and lowest values excluding outliers. The dotted line is the median. Outliers are defined as observations that are between 1.5 and 3 box lengths from the upper and lower edge of the box. Table 7 gives R&D decisions averaged over the whole experiment and the average of the last two R&D decisions, which corresponds with the last ten periods. In the contract treatments a distinction is made between average R&D decisions that are not contracted (specified by  $T_{010}$  and  $T_{110}$ ) and average contracted R&D decisions (specified by  $T_{011}$  and  $T_{111}$ ). Standard deviations are in brackets.

From the box plots we learn that R&D decisions without technological spillovers are generally very similar in the treatments without and with contract possibilities. The median is around 40 and thus lies somewhere between the competitive R&D level when expecting price competition in the second stage and the competitive R&D level when expecting price collusion. Another interpretation could be that it lies between the cooperative and competitive level, when price collusion is expected in the second stage. In table 7 a further distinction is made between average not-contracted and average contracted R&D decisions. Without spillovers, average contracted R&D decisions are below average not-contracted R&D decisions. The box plots of the treatments with spillovers show that R&D decisions of subjects having contract possibilities are higher than decisions of subjects without contract possibili-

	$\bar{X}_{1-35}$	$\bar{X}_{26-35}$
$\beta = 0$		
$T_{00}$	39.8 (5.0)	35.8 (6.7)
$T_{01}$	40.2 (10.5)	35.0 (7.8)
$T_{010}$	43.2 (10.0)	38.4 (5.0)
$T_{011}$	36.1 (11.0)	34.3 (9.2)
$\beta = 1$		
$T_{10}$	21.3 (9.3)	17.1 (9.3)
$T_{11}$	34.8 (9.7)	33.5 (8.4)
$T_{110}$	21.2 (13.7)	15.4 (14.1)
$T_{111}$	38.7 (9.4)	40.0 (11.8)

Table 7: Average duopoly R&D decisions and standard deviations

ties. With contract possibilities, R&D decisions definitely overshoot any of the benchmark R&D levels. Without contract possibilities, R&D decisions are around 20, which is either the cooperative R&D level assuming price competition in the second stage or between the competitive and cooperative level assuming price collusion in the second stage. The distinction between average not-contracted and average contracted R&D decisions, made in table 7, seems to matter especially for full spillovers. Average not-contracted R&D decisions in the contract treatment are very close to average R&D decisions in the baseline treatment. Average contracted R&D is much higher than average not-contracted R&D.

Each of the contract treatments ( $T_{01}$  and  $T_{11}$ ) have an outlying duopoly R&D decision. In  $T_{11}$ , the outlier is duopoly 15 and its behavior is close to competition in both stages. Behaviour of duopoly 12 in  $T_{01}$  is harder to classify. We can only observe that the R&D decision of this duopoly is higher than any of the benchmark levels.

Further, whether differences between treatments and within the contract treatments are statistically significant, is tested in a series of non-parametric tests. Within the contract treatments, differences in R&D behavior might arise between subjects that have actually used contract possibilities and those who have not, as table 7 showed. Expectations are that when contract possibilities are used, R&D levels are closer to the cooperative level. Results of Wilcoxon signed ranks tests of differences between contracted and non-contracted R&D decisions are in table 8 under the header ‘Within’. Results of Mann-Whitney tests of differences between the no-contract and contract treatments are under the header ‘Between’. Results are based on averages that are calculated for all periods and the last sub-period, i.e. the last ten periods. In the last row of each of the sub-periods, the number of observations

	Between		Within	
	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$
<i>All periods</i>				
z	-0.198 <sup>a</sup>	-2.984 <sup>a</sup>	-1.376 <sup>a</sup>	-2.701 <sup>a</sup>
exact sig. (2-tailed)	0.861	0.002	0.193	0.004
N	31	26	11	10
<i>Last 10 periods</i>				
z	-0.753 <sup>b</sup>	-3.349 <sup>a</sup>	-1.089 <sup>b</sup>	-2.207 <sup>a</sup>
exact sig. (2-tailed)	0.463	0.000	0.500	0.031
N	31	26	3	6

<sup>a</sup> based on  $X_1 - X_0 < 0$  where 1 is a dummy for contract.  
<sup>b</sup> based on  $X_1 - X_0 > 0$ .

Table 8: Mann-Whitney and Wilcoxon signed ranks test results for R&D

on which the related tests are based, is given.

The tests indicate that without technological spillovers, R&D levels do not differ between treatments with and without contract possibilities, which already could have been expected on the basis of the box plots and the descriptives in table 7. Also within the contract treatment without spillovers, no significant difference is found between contracted and non-contracted R&D levels. With technological spillovers, the tests yield a significant difference with significance levels of 5 or 1% between R&D levels in the two treatments and within the contract treatment, except in the first ten periods. More specifically, R&D levels are found to be higher when contracts are allowed compared to the baseline treatment. Furthermore, within the contract treatment, R&D levels are higher in periods in which contracts are made than in periods in which no contracts are made. This indicates that with high spillovers subjects are more cooperative in the R&D stage when they commit to an R&D contract, since cooperative R&D levels are above competitive R&D levels when spillovers are high. Note that when the outliers (cfr. box plots) are not taken into account in the tests, results are very similar.

The difference in results for the treatments with and without spillovers can have different causes. Do subjects sign less contracts without spillovers compared to with spillovers? Or do they simply fail to contract cooperative R&D levels? For this purpose, we tested whether the amount of chosen contracts differs between both treatments using a Mann-Whitney test. This test yields that, when all periods are taken into account, the amount of chosen contracts is significantly higher in the spillovers treatment than in the no-spillovers treatment. The corresponding p-value is 0.044. Leaving out the outliers does not change the results. Thus, evidence exists that with

complete spillovers, subjects commit more often to an R&D contract and are also more cooperative in R&D compared to without spillovers.

Finally, it should be examined whether the experimental R&D decisions coincide with the theoretical benchmarks. Difficulties arise, though, when comparing R&D decisions in the experiment with the benchmarks without taking into account pricing behavior. Let us make our point clear with an example. In treatment  $T_{00}$  the average duopoly R&D decision lies around 39. When comparing this figure with the theoretical benchmarks in table 1, no clear-cut conclusions on whether R&D is close to the cooperative or competitive level can be made. If subjects expected prices to be somewhere between the Nash and the cooperative level, we would say that R&D behavior in  $T_{00}$  is rather competitive, i.e. between 34.8 and 56.0. But if subjects expected that the future price would be at its cooperative level, we would conclude that R&D investment lies between the cooperative and the competitive level, i.e. between 26.0 and 56.0. That is why when testing the hypotheses related to R&D behavior of firms, also price decisions have to be taken into account. Based on the estimated long-run transformed prices and their confidence intervals of the previous section, further conclusions on R&D behavior in the first stage can be made. If it is assumed that the subjects act in the R&D stage taking into account their expected actions in the pricing stage and that their expected price decisions correspond to their actual price decisions, R&D behavior can indeed be identified.

It has been found in the previous section that prices are predominantly not at the Nash or cooperative level, which is indicated by the estimated long-run transformed prices (indicated by  $P$ ) lying somewhere between 0 and 1, and not being equal to 0 or 1. This naturally complicates the analysis of R&D decisions, since they cannot be simply compared to the theoretical benchmarks as presented in table 1 because these benchmarks are based on the assumption of individual or joint profit maximizing pricing behavior in the second stage. Finding a range of R&D benchmarks, i.e. theoretical competitive and cooperative R&D decisions, as a function of different values of  $P$  where  $0 \leq P \leq 1$ , would allow us to compare the experimental R&D decisions with the correct, corresponding R&D benchmarks. Setting up this range of R&D benchmarks can be done by reinterpreting the profit maximization problems in the second, i.e. the pricing, stage. More specifically, both second-stage individual and joint profit maximization problems can be unified into one modeling approach, which is the ‘coefficient of cooperation’ approach (Martin, 1993, p. 30). In this approach, both firms in a duopoly maximize their own profit and a fraction  $\phi$  of the profit of the competitor. Total profit to be maximized is then equal to  $\pi_i + \phi\pi_j$  for  $i, j = 1, 2$  and  $i \neq j$ . If  $\phi$  is equal to 0, individual profit maximization results in the pricing stage

and if  $\phi$  is equal to 1, price collusion results. For any value of  $\phi$  between 0 and 1, resulting prices are between the Nash and the collusive level, as is also the case for  $P$ . It can be shown that under the assumption of symmetry, the following relation exists between  $\phi$  and  $P$  (see appendix B),

$$P = \frac{2\phi(b - c)}{2b - c(\phi + 1)}, \quad (11)$$

where for any value of  $\phi$  between 0 and 1,  $P$  is increasing and convex in  $\phi$ . Since it is possible to establish theoretical R&D benchmarks for R&D competition and R&D cooperation, as a function of  $\phi$ , i.e. by solving the first- and second-stage profit maximization problems, it is also possible to write them as a function of  $P$ . Figure 3 contains for both spillover levels simulated curves of R&D benchmarks that represent the competitive and cooperative R&D levels (displayed as  $X^*$  and  $X^{**}$  respectively) for different values of  $P$ . As to compare the experimental R&D decisions with these theoretical benchmarks, averages of experimental R&D decisions<sup>11</sup> (see also table 7) are located in the graphs in the form of grey circles. Each of the circles combines the estimated long-run transformed price on the horizontal ax, i.e. the estimated  $P$  of a treatment (based on table 6), with the average R&D decision in that treatment, on the vertical ax.

The location of the average R&D decision that represents R&D in the treatment without spillovers and without contract possibilities and with contract possibilities in periods without R&D contracts (represented by  $T_{00} + T_{010}$  in figure 3) suggests that R&D behavior is competitive. To be competitive, average R&D should be between 37.4 and 42.0<sup>12</sup>. Without spillovers and with contract possibilities, in periods with R&D contracts ( $T_{011}$  in figure 3), average R&D is somewhat below the competitive level and does not lie within the competitive interval which is [41.1, 45.6]. With spillovers and without contract possibilities and in periods without R&D contracts in the contract treatment ( $T_{10} + T_{110}$  in figure 3), the average R&D decision is located on the curve representing R&D cooperation and lies within the cooperative interval, i.e. between 20.0 and 23.2. R&D decisions in contract periods in the contract treatment ( $T_{111}$  in figure 3) definitely overshoot the cooperative level.

At first sight, this overshooting might be hard to interpret, but it should be remarked that this might be the consequence of how the model on which

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<sup>11</sup>Average R&D decisions are used since there are too few observations in time on R&D decisions to do an econometric analysis.

<sup>12</sup>These benchmarks are calculated taking into account the estimated confidence intervals of the transformed price of table 6 and the re-interpretation of the second-stage maximization problem, as previously explained. This goes for other benchmarks referred to in what follows in this section.

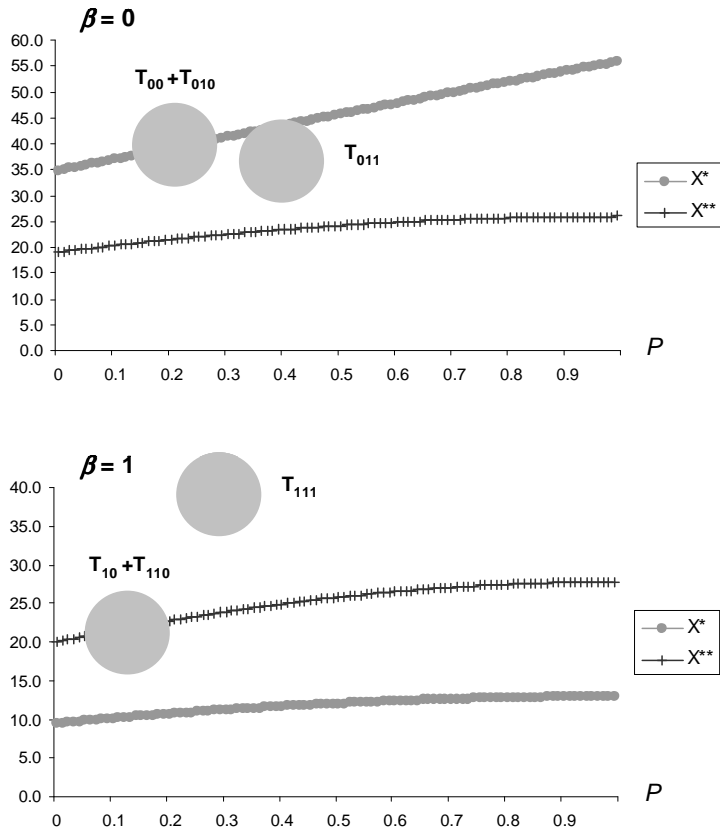


Figure 3: Simulations of competitive and cooperative R&D

the experiment is based, behaves. More specifically, as we already mentioned in section 3, the potential increase in profit that results from leaving a competitive R&D level for a cooperative R&D level is much smaller than the potential increase in profit that results from going from price competition to price cooperation. So changes in price decisions effect profits more than changes in R&D decisions, which is inherent to the underlying model. The overshooting in the spillovers treatment on the one hand and the insignificance of the difference in R&D decisions in the no-spillovers-treatment on the other hand, should be interpreted in this context.

To summarize, without spillovers subjects compete in R&D if they do not have R&D contract possibilities or if they do have contract possibilities but do not use them. R&D levels that are between the competitive and the cooperative one are chosen in periods where the contract possibilities are used. With technological spillovers, subjects cooperate in R&D if no R&D

contracts can be made and if they can be, but are not made. Contracted R&D overshoots the cooperative level. Thus, hypothesis 2 is rejected for the scenario with technological spillovers and not if no spillovers are present. Hypothesis 3 is rejected for both spillover levels. But these results should be interpreted with caution, since the sensitivity of profits with respect to R&D decisions is much smaller than with respect to price decisions.

## 6 Welfare

Finally, we compare total welfare, i.e. the sum of consumer and producer surplus, between and within the treatments. As consumer surplus is equal to  $U(q_1, q_2) - p_1q_1 - p_2q_2$  and producer surplus to  $\pi_1 + \pi_2$ , total welfare is equal to the following expression

$$W = U(q_1, q_2) - (\alpha - (x_1 + \beta x_2))q_1 - \delta \frac{x_1^2}{2} - (\alpha - (x_2 + \beta x_1))q_2 - \delta \frac{x_2^2}{2}. \quad (12)$$

In table 9 averages of total welfare are given for the different treatments and for periods without and with R&D contracts within the contract treatments. Without technological spillovers, welfare seems to be higher in the treatment without contract possibilities compared to the treatment with contract possibilities. Also, within the contract treatment, welfare in periods in which no R&D contracts were made is higher than in periods with R&D contracts. This highly corresponds to the conclusions based on the experimental price decisions. Indeed, higher prices yield lower welfare than lower prices, given that R&D decisions are constant. With technological spillovers, these conclusions cannot be made. Welfare is slightly higher in the contract treatment and in periods with R&D contracts than in the treatment without contract possibilities and periods without R&D contracts in the contract treatment respectively.

In table 10 results of statistical tests of differences in welfare between and within treatments are presented. The structure of the table is the same as the structure of similar tables in the previous subsections. These tests confirm that without technological spillovers, welfare in periods with R&D contracts is lower than welfare in periods without R&D contracts, within the contract treatment. Between the contract and the no-contract treatment, the difference in welfare fails to be statistically significant. With technological spillovers, differences in welfare between and within the treatments are not statistically significant at the 5% level. At the 10% level, welfare in the final 10 periods with R&D contracts is higher than welfare without R&D contracts, within the contract treatment.



	$W_{1-35}$	$W_{26-35}$
$\beta = 0$		
$T_{00}$	4563.2 (316.8)	4499.5 (415.4)
$T_{01}$	4390.8 (330.9)	4364.8 (422.2)
$T_{010}$	4646.2 (199.9)	4724.6 (137.6)
$T_{011}$	4269.9 (333.7)	4209.9 (419.0)
$\beta = 1$		
$T_{10}$	4758.0 (313.9)	4666.1 (291.9)
$T_{11}$	4848.7 (365.1)	4790.4 (353.7)
$T_{110}$	4824.2 (429.8)	4778.1 (374.6)
$T_{111}$	4886.2 (390.6)	4900.8 (453.3)

Table 9: Average welfare and standard deviations

	Between		Within	
	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$
<i>All periods</i>				
$z$	-1.621 <sup>a</sup>	-0.597 <sup>b</sup>	-2.934 <sup>a</sup>	-0.663 <sup>b</sup>
sig. (2-tailed)	0.110	0.574	0.003	0.508
N	31	26	11	10
<i>Last 10 periods</i>				
$z$	-1.383 <sup>a</sup>	-0.960 <sup>b</sup>	-1.604 <sup>a</sup>	-1.786 <sup>b</sup>
sig. (2-tailed)	0.175	0.357	0.109	0.075
N	31	26	3	6

<sup>a</sup> based on  $W_1 - W_0 < 0$  where 1 is a dummy for contract.

<sup>b</sup> based on  $W_1 - W_0 > 0$ .

Table 10: Mann-Whitney and Wilcoxon signed ranks test results for welfare

It is not that surprising, though, that welfare conclusions for the cases with technological spillovers are different from the cases without spillovers. Indeed, as has been shown in the previous subsection on R&D decisions, in the treatments without spillovers, no differences in R&D decisions have been found between or within treatment(s). As such, the relation between prices and welfare is quite straightforward, i.e. higher prices yield lower welfare. With spillovers, such a straightforward link between prices and welfare cannot be established, since R&D decisions in periods with R&D contracts (in the contract treatment) have been found to be significantly higher than R&D decisions in other periods and in the treatment without contract possibilities. Since a higher R&D level yields higher welfare, given that prices are constant, it is not surprising that welfare in periods with higher transformed prices

and R&D contracts that contain high R&D levels is higher than or does not significantly differ from welfare in periods with lower transformed prices and lower R&D levels.

## 7 Conclusion

In the paper we examined in an experiment whether in a duopoly framework with technological spillovers, cooperation in R&D facilitates price collusion. Subjects in the experiment were asked to make repeated R&D decisions in a first stage and price decisions in a second stage. For two scenarios of technological spillovers, i.e. no spillovers versus complete spillovers, a treatment without binding R&D contract possibilities and a treatment with contract possibilities were run. A first finding is that prices are almost never at the subgame perfect Nash level, instead they are usually higher and lie between the Nash and the collusive level. This is contrary to what theory predicts, which is individual profit maximization in the second stage, irrespective of whether firms have possibilities to commit to R&D contracts in the first stage. In this context the question can be raised whether backward induction, which is the method of solving the two-stage model and necessary to establish the theoretical predictions, is valid in the laboratory.

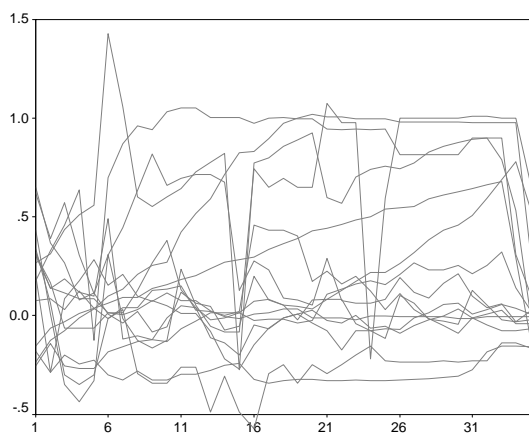
A second finding is that if no technological spillovers are present, laboratory prices in periods in which R&D contracts were committed to, are higher than prices in periods without R&D contracts. A fully collusive price level is generally not reached, though. With complete spillovers, such a difference in absolute price levels is not found. If it is taken into account that the theoretical price predictions depend on the first-stage R&D decisions and prices are normalized, it is found that also with spillovers, higher prices are gathered when contracts are committed to.

Further, regarding the laboratory R&D decisions we find that without technological spillovers and with contract possibilities, competitive levels prevail in periods where no R&D contracts are committed to. Without contract possibilities, R&D is somewhat lower and thus between the competitive and the cooperative level. Contracted R&D levels in the contract treatment are still lower and closer to the cooperative R&D level. With technological spillovers, non-contracted R&D decisions—either in the treatment with or without contract possibilities—are at the joint profit maximizing level and contracted R&D decisions overshoot the joint profit maximizing level. Thus, taking into account that cooperative R&D in industries without (with) technological spillovers is lower (higher) than competitive R&D, evidence exists that the ‘natural’ tendency to cooperate in R&D is higher with complete

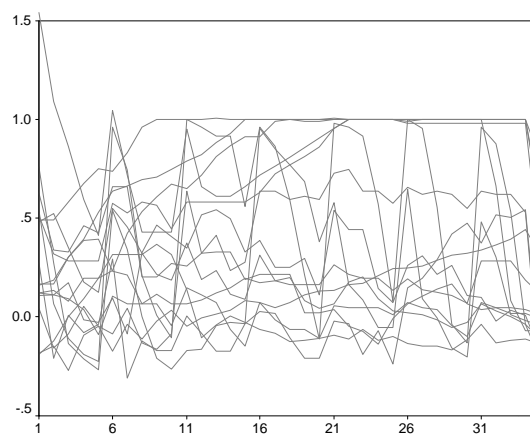
spillovers compared to without spillovers, which is a result that coincides with Suetens (2003b).

As to provide some policy conclusions, it is important to take into account of how welfare is affected by the price and R&D decisions. Without technological spillovers, it is clear that welfare in periods in which R&D contracts are committed to is lower than in periods without contracts. With full spillovers, no such difference in welfare exists. The reason is that —given that R&D levels that are higher than theoretical competitive or cooperative predictions, yield higher welfare— in contract periods, next to transformed prices, R&D decisions are also higher, which reverses the negative effect of high transformed prices on welfare. For governments that have recently been lenient in their anti-trust legislation toward the formation of R&D agreements and research joint ventures between firms, the findings in the lab should provide a warning. Cooperative R&D agreements apparently can carry over to the product market stage which can result in a decrease in welfare if there exist no technological spillovers between the firms.

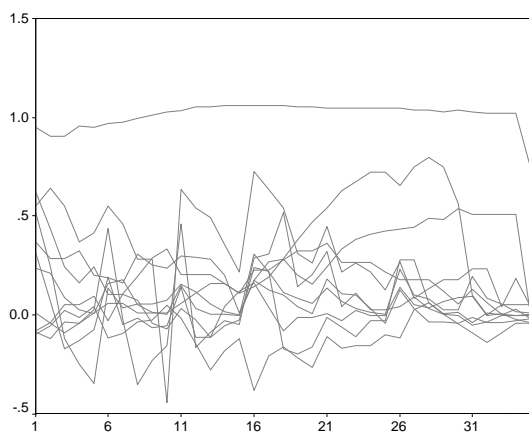
## Appendix A: Transformed duopoly prices



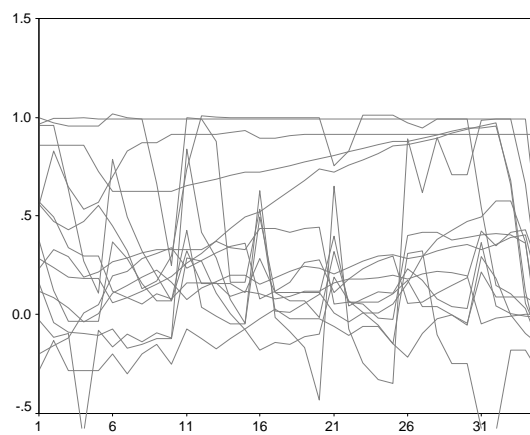
$T_{00}$



$T_{01}$



$T_{10}$



$T_{11}$

## Appendix B: The ‘coefficient of cooperation’ approach

In the ‘coefficient of cooperation’ approach, a firm maximizes its own profit and a part  $\phi$  of the other firm’s profit which coincides with the following second-stage maximization problem for  $i = 1, 2; j = 1, 2; i \neq j$ :

$$\max_{p_i} \pi_i + \phi \pi_j.$$

The price that solves this problem is

$$p_i = \frac{[2b + c(1 + \phi)][a(b - c) + \alpha(b - c\phi)] - \dots}{4b^2 - c^2(1 + \phi)^2} \\ - \frac{x_i[2b^2 + b\beta c(1 - \phi) - c^2\phi(1 + \phi)] - \dots}{-x_j[2b^2\beta + bc(1 - \phi) - \beta c^2\phi(1 + \phi)]}.$$

When  $\phi = 0$ ,  $p_i$  is equal to the Nash price level that maximizes individual profit, called  $p_i^{Nash}$  and when  $\phi = 1$ ,  $p_i$  is equal to the cooperative price level that maximizes joint profit, called  $p_i^{Collude}$ .

Define the transformed price of firm  $i$   $P_i$  as follows,

$$P_i = \frac{p_i - p_i^{Nash}}{p_i^{Collude} - p_i^{Nash}}. \quad (13)$$

Note that at this step prices need not necessarily be symmetric. The index  $i$  in equation 13 refers to the  $i$ th firm in the duopoly, while the indices  $k$  and  $t$  in equation 8 referred to the duopoly and the period in the *experiment*. Transformed (experimental) prices in equation 8 are calculated on the basis of *per duopoly* average prices. The filling in of  $p_i, p_i^{Nash}$  and  $p_i^{Collude}$  in the expression of  $P_i$ , and the assumption of symmetry in the first stage, i.e.  $x_i = x_j$ , yields symmetric prices and the following expression for  $P = P_i = P_j$ ,

$$P = \frac{2\phi(b - c)}{2b - c(\phi + 1)},$$

where  $P$  is increasing and convex in  $\phi$  for  $0 < \phi < 1$ .

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