

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

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Abstract

We examine whether R&D cooperation facilitates tacit price collusion in a laboratory setting based on a two-stage R&D model with product market competition. For two scenarios of technological spillovers (no versus complete spillovers), a baseline treatment without binding contract possibilities and a contract treatment where it is possible to credibly commit to an R&D contract, are run. We find that, for both spillover levels, the degree of price collusion in the contract treatments is significantly higher in periods where R&D contracts are committed to than in periods without contracts and than in the baseline treatments, without reaching the fully collusive level.

JEL codes: C90, L13, O31.

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

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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. On the other hand, 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 theoretical underpinning for the encouragement of R&D cooperation is provided by d'Aspremont and Jacquemin (1988) and many others (see e.g. Kamien et al., 1992; Suzumura, 1992; Brod and Shivakumar, 1997; Petit and Tolwinski, 1999; Hinlopen, 2003). It is generally agreed on that R&D cooperation enhances social welfare if pre-cooperative or at least post-cooperative technological spillovers amongst the cooperating firms are high enough, given that Cournot or Bertrand competition prevails in the product market.

These models assume that firms interact once in the R&D stage and the product market and predict that they behave according to the subgame perfect Nash (SPN) equilibrium. An empirically relevant question is whether the assumption of Cournot or Bertrand competition in the product market can be maintained if firms are allowed to cooperate in R&D and repeatedly interact in both stages (see e.g. Vonortas, 2000). Collusion in the output stage might be facilitated under these conditions.

In this paper we investigate the question whether cooperation in cost-reducing R&D enhances price collusion in an experiment. Using the laboratory method, we are able to unambiguously focus on the simple relation between R&D cooperation and price collusion. The interactions in the experiment are based on a static non-tournament duopoly model with two stages, an R&D stage and a pricing stage. Given that in the real world, firms are able to engage in cooperative R&D projects more than once and repeatedly interact in the product market, the static game is repeated a finite number of times. Moreover, R&D decisions usually have a medium- or long-term character and are thus less frequently taken than price decisions. Therefore, R&D decisions in the experiment remain constant for a number of periods, while prices may vary in each period.

Treatments where subjects have the possibility to make binding R&D agreements in the R&D stage are compared with baseline treatments without any contract possibilities. In the second stage, i.e. the product market, no binding commitments are allowed. Given the importance of the level of technological spillovers in the non-cooperative and cooperative R&D literature, a distinction is also made between a scenario without spillovers and a scenario with full spillovers.

For both spillover scenarios we find that the degree of cooperation in the pricing stage is generally higher in the contract treatments than in the baseline treatments. Moreover, we find strong evidence for the degree of price cooperation to be higher in the contract treatments when R&D contracts are committed to than when not committed to.

Examples of other laboratory experiments where subjects make R&D and price/quantity decisions are Isaac and Reynolds (1992) and Jullien and Ruffieux (2001). Both are dynamic experiments and focus on the evolution of market prices in a setting where (stochastic) non-cooperative R&D decisions can be made. Neither of the experiments contains a possibility for participants to commit to binding R&D contracts.

Some have provided a theoretical framework, somewhat different from the one in the above mentioned strand of literature, to investigate the question whether R&D cooperation facilitates cooperation in the product market. In Martin (1995) e.g. the effects of self-enforcing 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 patent race is infinitely repeated and it is assumed 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. The author finds that self-enforcing R&D cooperation 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. We are not aware of any empirical papers that examine whether cooperation in the product market is actually enhanced by R&D cooperation.

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 analyse the experimental prices and R&D decisions 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)¹. 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 $i \neq j$ ². The firms first decide on R&D investment and then on prices. Investing in R&D reduces unit production cost and has decreasing returns.

It is further assumed that technological spillovers may arise that reduce the unit cost of the competitor. Replacing quantities by the direct demand curves yields the following profit function of firm i for $i = 1, 2$ 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 . β represents the spillover parameter that lies between 0 and 1, α 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 ($x_i + \beta x_j$) 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. Therefore, in the R&D cost function, $\delta = \gamma(1 + \beta)$, where γ 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 AJ³.

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 SPN 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

¹Henceforth KMZ and AJ.

²The 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).

³In 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.

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 SPN 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 equilibrium⁴:

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

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 R&D. Restricting the solution to be symmetric yields the following unique cooperative outcome⁵:

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

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, the benchmark case of price collusion is looked at. 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 SPN 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

⁴It is assumed that the second-order conditions and the stability conditions suggested by Henriques (1990) are met.

⁵It 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.

	x^*	x^{**}	p^*	p^{**}	π^*	π^{**}	W^*	W^{**}
Price competition								
$\beta = 0$	17.4	9.5	85.3	91.2	862.6	891.0	4779.6	4614.0
$\beta = 1$	4.8	10.0	91.2	83.3	913.8	936.8	4657.5	5003.6
Price collusion								
$\beta = 0$	28.0	13.0	133.5	141.0	1112.1	1214.2	3713.6	3723.4
$\beta = 1$	6.5	13.9	141.0	133.6	1254.6	1300.7	3804.2	4087.6

Table 1: Theoretical benchmarks

of the collusive prices. This yields other predictions for the competitive and cooperative R&D levels. These are respectively

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

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

The theoretical benchmarks that correspond to the parameters chosen in the experiment are in table 1. The parameters satisfy stability conditions (Henriques, 1990) and conditions for R&D solutions to be symmetric (Salant and Shaffer, 1998). In the scenario without technological spillovers, R&D cooperation yields a reduction in welfare, given that firms compete in prices in the second stage. On the contrary, with complete spillovers welfare is increased under R&D cooperation. If firms collude in prices, welfare is always lower compared to when they would compete.

It is clear that, irrespective of whether binding R&D agreements can be made in the first stage, theory predicts that prices are at their SPN level. Additionally, with respect to the R&D stage, predictions are that R&D investment is at the SPN level if no binding R&D agreements can be made and at the cooperative level if R&D agreements can credibly be committed to.

3 Experimental procedure

The experiment was run at Tilburg University and consisted of six computerized sessions with a total number of 114 recruited students. The software *z-Tree* developed by Fischbacher (1999) has been used. Students were undergraduate students in economics, law or social sciences and participated before in other types of experiments. Each session lasted for two hours and earnings were between 11.5 and 30.5 EUR. Before the experiment started,

instructions (see appendix A) were handed out and the students had the opportunity to ask questions. During the trial periods, instructions were clarified aloud.

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. The experiment consisted of four treatments; a baseline treatment without contract possibilities (*BASE*) and a treatment with contract possibilities (*CON*), both for $\beta = 0$ and $\beta = 1$. 30 students participated in *BASE*, $\beta = 0$, 22 in *BASE*, $\beta = 1$, 32 in *CON*, $\beta = 0$ and 30 in *CON*, $\beta = 1$. This yielded a total of 57 duopolies of which 15 are in *BASE*, $\beta = 0$, 11 in *BASE*, $\beta = 1$, 16 in *CON*, $\beta = 0$ and 15 in *CON*, $\beta = 1$.

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 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 behaviour 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 decisions 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 conditions.

The subjects 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 to get acquainted with the computer program. The decisions that were made in the practice rounds 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. This may be motivated by the medium-

or long-term character of R&D investment decisions in reality compared to price decisions. Moreover, when subjects were to make two (R&D and price) decisions in each period, it would have been very hard for them to judge whether profit changes result from changes in R&D or in 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 and subjects were informed about this exchange rate. Duopolies were fixed during the experiment and subjects had no knowledge of the identity of their counterparts.

Subjects were explained that the investment reduced unit production cost by the amount of the investment (and 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)⁶ 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 that enabled subjects to send a symmetric contract proposal to the other player. The contract was binding in that once a contract was accepted, 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 new 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. The amount of contract proposals was not limited.

4 Experimental data

Our analysis focuses on comparisons of decisions in treatments with the theoretical predictions and on comparisons between and within treatments. As to get independent observations within treatments, all descriptive and statistical analyses are based on duopoly-specific variables, such as e.g. average

⁶The parameter value of γ has been set to 0.96, such that $\delta \approx 1$ when no spillovers are present and $\delta \approx 2$ for complete spillovers.

duopoly prices or R&D decisions. It is beyond the scope of the paper to explore individual-specific R&D or pricing strategies, nor is it the aim to analyse convergence processes of duopoly decisions in detail. We first provide an analysis of the price decisions, then of the R&D decisions and finally of welfare.

4.1 Prices

Descriptive analysis

Averages of duopoly prices are in table 2⁷. Averages are calculated in four different ways and presented in separate columns. The first average is based on all observations in the experiment. The second average is only based on the last ten periods, as to focus on decisions when subjects have gathered a lot of experience with making decisions. The third average (represented by \bar{P}_{5th} in the table) is based on the last periods of each set of five subsequent periods with a constant R&D decision, given the cyclical pattern of prices (see figure 1) and possible end-cycle effects. Finally, we also present averages that are only based on price decisions in the final period (period 35) of the experiment.

Within the contract treatment, a further distinction is made on the basis of whether a contract has actually been chosen or not, which is referred to by *CON0* and *CON1*⁸. *CON1* refers to averages of prices in periods where R&D contracts were committed to⁹ and *CON0* to averages of prices in periods without R&D contracts. Note that the standard deviations only give an indication of cross-sectional heterogeneity, i.e. across duopolies, and not of heterogeneity of prices in time¹⁰.

Without spillovers, prices in the treatment with contract possibilities are higher than prices in the treatment without contract possibilities. Further, within the contract treatment without spillovers, prices in periods where

⁷In 14 out of 1995 (57*35) cases, prices were chosen that yielded a negative production quantity. These observations were left out of all descriptive tables and data analyses. Leaving them out had no effect on any of the conclusions made.

⁸Averages referred to by *CON* refer to weighted averages of *CON0* and *CON1* where the weights are the number of observations in *CON0* and *CON1* respectively. These averages are not necessarily the same as average (price or R&D) decisions in the contract treatment without taking into account whether or not contracts were committed to. This goes also for other tables with descriptive statistics.

⁹The calculation of averages in periods with R&D contracts is based on all periods of each set of five subsequent periods where an R&D contract has been committed to, and thus not only on the first.

¹⁰All averages are actually averages of average duopoly R&D decisions calculated in different sets of periods.

Treatment	\bar{p}_{1-35}	\bar{p}_{26-35}	\bar{p}_{5th}	\bar{p}_{35}
$\beta = 0$				
<i>BASE</i>	94.5 (18.9)	99.5 (23.5)	92.6 (18.4)	88.8 (14.2)
<i>CON</i>	99.5 (18.5)	103.3 (22.2)	95.0 (19.4)	89.9 (19.5)
<i>CON0</i>	88.8 (10.7)	87.2 (8.6)	86.5 (13.2)	79.7 (5.6)
<i>CON1</i>	111.0 (18.4)	114.9 (22.0)	104.2 (21.2)	96.1 (6.7)
$\beta = 1$				
<i>BASE</i>	93.5 (16.0)	96.6 (14.3)	91.3 (15.7)	90.8 (10.2)
<i>CON</i>	89.0 (17.1)	90.9 (20.2)	85.2 (17.7)	75.2 (17.7)
<i>CON0</i>	81.8 (9.3)	85.5 (7.9)	81.5 (8.6)	86.3 (22.5)
<i>CON1</i>	93.3 (19.4)	93.1 (23.3)	87.4 (21.4)	73.5 (18.4)

Table 2: Average prices and standard deviations

R&D contracts were actually committed to are higher than in periods without R&D contracts.

Prices in the scenario with technological spillovers are generally not that different between the baseline and contract treatments. In the final period prices in the contract treatment seem to be significantly lower than in the baseline treatment. Within the contract treatment, a similar conclusion as in the treatment without spillovers can be made, although that in the final ten periods, the gap in prices seems to tighten. In period 35 prices in periods with contracts even become lower than prices in periods without contracts.

Since theoretical SPN and collusive prices are expressed in terms of own and other firm's R&D, subjects got most likely locked in local optima having made their R&D decisions. This implies that if the R&D decision of a pair in the experiment is not at a level that corresponds to a theoretical R&D benchmark, the theoretical prediction of the price that corresponds to this R&D decision cannot be at any benchmark level presented in table 1. 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. Thus, for each combination of R&D decisions within a duopoly, 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

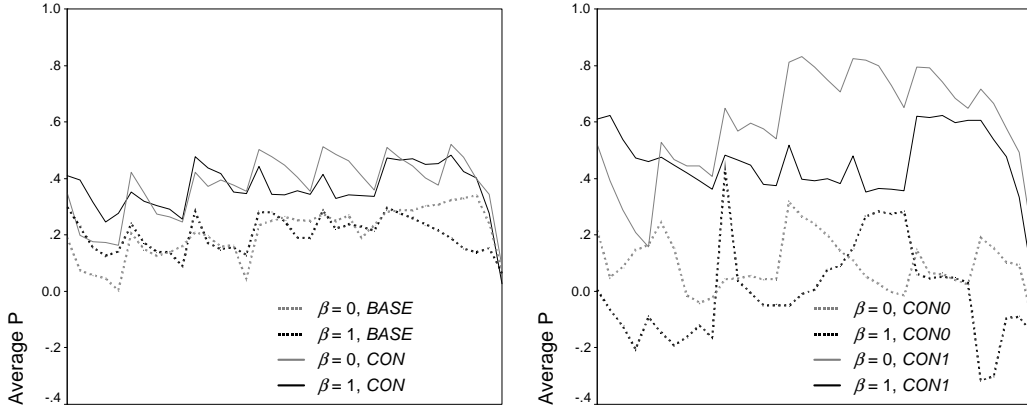


Figure 1: Evolution of average P

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 bars refer to averages of individual prices of the two subjects within duopoly k , t to the period and indices $Nash$ and $Collude$ refer to the Nash price prediction based on equation 2 and the collusive price based on equation 5 respectively. P_{kt} measures the degree of price collusion. 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 between the Nash and the cooperative level, P_{kt} is between 0 and 1.

The evolution of average degrees of price collusion is in figure 1 (see appendix B for time graphs of all duopolies). For convenience we simply apply the notation P to indicate the degree of price collusion. 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 $CON0$ and $CON1$. 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 averages in periods with and averages in periods without R&D contracts. A first observation is that average degrees of price collusion gradually increase during the experiment and fall in the last period of the experiment, which could be due to an end effect. Further, the cyclical pattern of the series in the figure indicates that within each five periods with a constant R&D decision, the degree of price collusion usually declines towards the final of the five periods. These

Treatment	\bar{P}_{1-35}	\bar{P}_{26-35}	\bar{P}_{5th}	\bar{P}_{35}
$\beta = 0$				
<i>BASE</i>	0.21 (0.33)	0.28 (0.41)	0.17 (0.32)	0.07 (0.25)
<i>CON</i>	0.30 (0.32)	0.35 (0.38)	0.21 (0.35)	0.09 (0.33)
<i>CON0</i>	0.12 (0.19)	0.06 (0.14)	0.08 (0.24)	-0.09 (0.10)
<i>CON1</i>	0.49 (0.33)	0.56 (0.37)	0.36 (0.39)	0.20 (0.38)
$\beta = 1$				
<i>BASE</i>	0.20 (0.30)	0.20 (0.31)	0.16 (0.30)	0.06 (0.23)
<i>CON</i>	0.25 (0.32)	0.29 (0.35)	0.18 (0.31)	0.03 (0.30)
<i>CON0</i>	-0.03 (0.13)	-0.03 (0.18)	-0.03 (0.12)	-0.15 (0.22)
<i>CON1</i>	0.41 (0.29)	0.43 (0.31)	0.31 (0.32)	0.06 (0.31)

Table 3: Average P and standard deviations

observations closely correspond to behaviour in earlier experiments on finitely repeated games (see e.g. Selten and Stoecker, 1986).

Averages and standard deviations of the degree of price collusion are in table 3. Standard deviations in the table again give only an indication of cross-sectional heterogeneity, and not of heterogeneity of prices in time (see appendix C for duopoly-specific data with standard deviations that refer to within-duopoly variation).

The figure and table show that the degree of price collusion in the scenario without spillovers closely correspond to the scenario with spillovers, in both baseline and contract treatment. A relatively higher level of price collusion is observed in contract treatments when R&D contracts were made. When no contracts were made (in contract treatments), prices seem to be quite close to the Nash level. In the baseline treatments, P is slightly above the Nash level. In the final period price collusion disappears in and within all treatments and prices decline towards the Nash level. Finally, standard deviations are quite high, which indicates that large differences exist across the different duopolies' pricing strategies.

Statistical analysis

We first discuss results of tests for differences in degree of price collusion (P) between and within treatments. Results of Mann-Whitney tests of differences between treatments without and with complete technological spillovers ($\beta = 0$ versus $\beta = 1$) are in table 4. Column *BASE* contains the result of a difference test between the baseline treatments (*BASE*, $\beta = 0$ versus *BASE*, $\beta = 1$) and columns *CON0* and *CON1* refer to the test results with respect to the degree of price collusion in the contract treatments in periods where no R&D contracts were committed to (*CON0*, $\beta = 0$ versus

	<i>BASE</i>	<i>CON0</i>	<i>CON1</i>
<i>Periods 1-35</i>			
sig. (2-tailed)	0.938	0.266	0.534
N	26	24	28

Table 4: Spillover treatment effects for prices: non-parametric test results

CON0, $\beta = 1$) and in periods with R&D contracts (*CON1*, $\beta = 0$ versus *CON1*, $\beta = 1$) respectively. Only results based on averages over all periods are presented since results of the tests using other sub-sets of periods are the same. Clearly, as can be read from the table, for none of the treatments significant differences exist in the extent of price collusion between $\beta = 0$ and $\beta = 1$ ¹¹.

We further tested whether differences in P between the baseline and the contract treatments and within the contract treatments are statistically significant. The between-treatment comparisons are based on Mann-Whitney tests of differences between *BASE* and *CON* (without distinguishing on the basis of whether contracts were made), between *BASE* and *CON0* (based on periods without contracts) and between *BASE* and *CON1* (based on periods with contracts). Test results are in table 5. We ran the test for four different sets of periods; all periods, the last ten periods, the final period of each group of five periods with a constant R&D decision and period 35 (the final period). Moreover, we present general results —without distinguishing between the two levels of technological spillovers— as well as separate results for both spillover levels ($\beta = 0$ and $\beta = 1$). The presentation of the general results is justified, since non-parametric tests do not find significant differences in the degree of price collusion between $\beta = 0$ and $\beta = 1$ (see table 4).

The Mann-Whitney statistics based on all observations indicate that a significant difference (5% significance) in degree of price collusion exists between the baseline and contract treatments, implying that in contract treatments the degree of price collusion is generally higher than in baseline treatments. This difference is less pronounced when only considering the last ten periods (10% significance). When only taking into account the final period or the final periods of all groups of five periods with a constant R&D decision, the statistical significance disappears. This is not surprising, given that prices often fall in the final period of the experiment and towards the end of each five-periods-cycle. The significance of the between-tests of *BASE* versus

¹¹The statistics are all based on negative ranks, which implies that the sum of ranks is always higher when $\beta = 0$ than when $\beta = 1$ such that $H_1 : P_{\beta=0} \stackrel{>}{\neq} P_{\beta=1}$.

	<i>BASE – CON</i>			<i>BASE – CON0</i>			<i>BASE – CON1</i>		
	all	$\beta = 0$	$\beta = 1$	all	$\beta = 0$	$\beta = 1$	all	$\beta = 0$	$\beta = 1$
<i>Periods 1-35</i>									
sig. (2-tailed)	0.037 ^b	0.133 ^b	0.154 ^b	0.100 ^a	0.570 ^a	0.063 ^a	0.004 ^b	0.040 ^b	0.052 ^b
N	57	31	26	49	29	20	54	28	26
<i>Periods 26-35</i>									
sig. (2-tailed)	0.073 ^b	0.236 ^b	0.139 ^b	0.140 ^a	0.478 ^a	0.159 ^a	0.012 ^b	0.073 ^b	0.052 ^b
N	57	31	26	40	23	17	52	26	26
<i>Final periods of groups of 5 periods</i>									
sig. (2-tailed)	0.200 ^b	0.527 ^b	0.203 ^b	0.041 ^a	0.315 ^a	0.074 ^a	0.045 ^b	0.147 ^b	0.154 ^b
N	57	31	26	49	29	20	54	28	26
<i>Period 35</i>									
sig. (2-tailed)	0.357 ^a	0.607 ^a	0.533 ^a	0.024 ^a	0.073 ^a	0.374 ^a	0.968 ^a	0.579 ^a	0.664 ^b
N	57	31	26	34	21	13	49	25	24

^a $H_1 : P_{CON.} < P_{BASE.}$; ^b $H_1 : P_{CON.} > P_{BASE.}$

Table 5: Contract treatment effects for prices: non-parametric test results

CON also disappears when the tests are separately run for both spillover levels.

The between-comparisons of *BASE* and *CON0* yield no significant difference in degree of price collusion between the baseline treatment and periods without contracts in the contract treatments. In the final period of the experiment or the fifth periods of the five-periods-cycles, the degree of price collusion is significantly lower in *CON0* than in *BASE*. The significance again disappears or greatly reduces when considering both spillover scenarios separately.

The test results of the comparison of *BASE* with *CON1* provide evidence for the degree of price collusion in periods with R&D contracts in the contract treatments to be generally higher than in the baseline treatments, also when subjects have gained lots of experience (in the last ten periods). The significance only slightly reduces when considering the spillover treatments separately, or when considering final periods of five-periods-cycles. When only considering the final period the significance again disappears.

Thus, summarizing the between-test results, we find that in the contract treatments the degree of price collusion generally is significantly higher than in the baseline treatments. The difference is more pronounced when only taking into account periods where contracts were actually committed to. In the final period of the experiment the difference disappears. If it is assumed that behaviour in the final period is similar to behaviour in the one-shot R&D and pricing game, we can conclude that repeating the game is necessary to find an effect of R&D cooperation on price collusion.

Next, we turn to statistical test results of comparisons of *P* within contract treatments. Table 6 contains results of Wilcoxon signed-ranks tests of

	all	$\beta = 0$	$\beta = 1$
<i>Periods 1-35</i>			
sig. (2-tailed)	0.000	0.006	0.008
N	21	11	9
<i>Periods 26-35</i>			
sig. (2-tailed)	0.011	0.109	0.046
N	9	3	6
<i>Final periods of groups of 5 periods</i>			
sig. (2-tailed)	0.003	0.037	0.011
N	21	11	9
$H_1 : P_{CON1} > P_{CON0}$.			

Table 6: Non-parametric tests of $H_0 : P_{CON1} = P_{CON0}$

comparisons between $CON0$ with $CON1$. These tests are based on price decisions of duopolies that switched between committing and not committing to an R&D contract in the related sub-set of periods. Decisions of duopolies that either never or always signed a contract in that sub-set of periods, necessarily drop out of the within-analysis, which explains the reduction in the number of observations (N) in the table compared to the between-analyses. Naturally, the within-tests cannot be performed for the final period (period 35) of the experiment since switching between not committing and committing to an R&D contract during one decision period could not occur.

The degree of price collusion is generally significantly higher in periods with R&D contracts than prices in periods without contracts. When considering the spillover levels separately, the significance in the last ten periods decreases, probably because there are too few observations. For instance for $\beta = 0$, only 3 observations underlay the Wilcoxon test in the last ten periods, implying that 3 out of 16 duopolies switched between choosing and not choosing an R&D contract in the last ten periods. Furthermore, the test results for the final periods of five-periods-cycles also indicate that the degree of price collusion in periods with contracts is higher than in periods without contracts. This suggests that the degree of price collusion not only increases in the periods that directly follow the actual contracting decision, but also stay at the higher level until the end of each five-periods-cycle.

Further, we test whether the degree of price collusion significantly differs from 0 and 1, corresponding to the Nash and the collusive level respectively, for the different treatments. Therefore, we performed Wilcoxon signed-ranks tests to compare the duopoly averages of P taken on the basis of different sub-sets of periods with SPN behaviour (0) and full price collusion (1)¹².

¹²Given the cross-sectional and time-series nature of the experimental data, one would

	<i>BASE</i>		<i>CON0</i>		<i>CON1</i>	
	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$
<i>Periods 1-35</i>						
sig. (2-tailed)	0.017 ^a	0.016 ^a	0.019 ^a	0.859 ^a	0.001 ^a	0.001 ^a
N	15	11	14	9	13	15
<i>Periods 26-35</i>						
sig. (2-tailed)	0.047 ^a	0.010 ^a	0.263 ^a	0.917 ^a	0.004 ^a	0.001 ^a
N	15	11	8	6	11	15
<i>Final periods of groups of 5 periods</i>						
sig. (2-tailed)	0.044 ^a	0.114 ^a	0.272 ^a	0.441 ^a	0.009 ^a	0.004 ^a
N	15	11	14	9	13	15
<i>Period 35</i>						
sig. (2-tailed)	0.776 ^a	0.929 ^a	0.075 ^b	0.655 ^b	0.169 ^a	0.972 ^b
N	15	11	6	2	10	13

^a $H_1 : P \gtrless 0$; ^b $H_1 : P \lesseqgtr 0$.

Table 7: Non-parametric tests of $H_0 : P = 0$

We only present the test results of the hypothesis $H_0 : P = 0$ because $H_0 : P = 1$ is always rejected with a significance level of 1% such that P is always significantly different from (smaller than) 1. Results are in table 7.

As the table shows, prices in the baseline treatments are mostly significantly different from (above) the SPN level. The significance reduces or disappears in the final period and in the fifth periods of cycles of five periods. In the *CON* treatment, $H_0 : P = 0$ is generally not rejected for most sub-sets of periods when only taking into account periods where R&D contracts were not committed to. Only for $\beta = 0$, the degree of price collusion averaged over all periods is significantly higher than 0. In periods where contracts are committed to, on the other hand, prices are generally significantly different from (larger than) the SPN level, even in the final periods of five-periods-cycles with a constant R&D decision. This suggests that although prices decline somewhat or move in the direction of the SPN level during each five-periods-cycle where the R&D decision remains constant, the effect that R&D cooperation (committing to R&D contracts) increases prices above the Nash level does not disappear at the end of each cycle. In period 35, prices in all treatments do not significantly differ from the SPN prediction, irrespective of whether R&D contracts are committed to.

think that a pooled econometric analysis where a representative price is estimated for each treatment, would be a more appropriate method of analysis. But since price decisions and convergence processes are very heterogeneous across duopolies, as shown in the graphs in appendix B, pooled econometric estimations would suffer a lot from misspecification. Therefore we opted for a more robust approach.

To summarize, introducing R&D contract possibilities in a finitely repeated R&D and pricing game, yields a higher degree of price collusion compared to a setting without contract possibilities. An important condition for the degree of price collusion to increase and remain at a higher level in the contract treatment, is that R&D contracts are actually committed to. In periods without R&D contracts actually committed to, prices are generally close to the SPN level and sometimes even fall below prices in the baseline treatments. This may indicate that subjects ‘punish’ each other and themselves for not having reached a satisfactory R&D agreement by lowering their prices even below a level that would normally have been reached without contract possibilities.

4.2 R&D decisions

In this section we focus on R&D behaviour in the experiment. Table 8 presents average R&D for the whole experiment and the last ten periods (final two R&D decisions)¹³. Standard deviations are in brackets and again refer to heterogeneity across duopolies.

From table 8 we learn that R&D decisions without technological spillovers are generally very similar in the treatments without and with contract possibilities. The averages are somewhat above the competitive R&D level when expecting price competition in the second stage. Another interpretation could be that they are between the cooperative and competitive level, when price collusion is expected in the second stage.

In the contract treatment without spillovers, average contracted R&D decisions are below average not-contracted R&D decisions. With spillovers, R&D decisions of subjects having contract possibilities are higher than decisions of subjects without contract possibilities. With contract possibilities, R&D decisions definitely overshoot any of the benchmark R&D levels. Without contract possibilities, R&D decisions are at a level close to 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. Furthermore, 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.

Further, whether differences between treatments and within the contract

¹³Averages based on other sub-sets of periods are superfluous. First, averages of R&D in period 35 and their standard deviations are very similar to averages based on the final two R&D decisions (final ten periods). Second, averages based on the final period of each cycle of five periods with a constant R&D decisions are naturally the same as averages based on all periods since R&D decisions remain constant during each set of five periods.

	\bar{x}_{1-35}	\bar{x}_{26-35}
$\beta = 0$		
<i>BASE</i>	19.8 (2.5)	17.9 (3.4)
<i>CON</i>	19.9 (5.5)	18.0 (3.9)
<i>CON0</i>	21.6 (5.0)	19.2 (2.5)
<i>CON1</i>	18.1 (5.5)	17.2 (4.6)
$\beta = 1$		
<i>BASE</i>	10.7 (4.7)	8.6 (4.7)
<i>CON</i>	15.9 (7.2)	16.5 (8.3)
<i>CON0</i>	10.2 (7.1)	7.7 (7.1)
<i>CON1</i>	19.4 (4.7)	20.0 (5.9)

Table 8: Average duopoly R&D decisions and standard deviations

	Between		Within	
	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$
<i>Periods 1-35</i>				
sig. (2-tailed)	0.843 ^b	0.003 ^b	0.169 ^d	0.008 ^d
N	31	26	11	9
<i>Periods 26-35</i>				
sig. (2-tailed)	0.451 ^a	0.001 ^b	0.276 ^c	0.027 ^d
N	31	26	3	6
^a $H_1 : x_{CON} < x_{BASE}$; ^b $H_1 : x_{CON} > x_{BASE}$.				
^c $H_1 : x_{CON1} < x_{CON0}$; ^d $H_1 : x_{CON1} > x_{CON0}$.				

Table 9: Contract treatment effects for R&D: non-parametric test results

treatments are statistically significant, is tested in a series of non-parametric tests. Within the contract treatments, differences in R&D behaviour might arise between subjects that have actually used contract possibilities and those who have not, as table 8 showed. Expectations are that when contract possibilities are used, R&D levels are closer to the cooperative level. Without spillovers this would imply that contracted R&D investment is lower than non-contracted R&D, while with spillovers it should be higher.

Results of Mann-Whitney tests of differences between the baseline and contract treatments are in table 9 under the header ‘Between’¹⁴. Results of Wilcoxon signed ranks tests of differences between contracted and non-contracted R&D decisions within the contract treatments are under the header ‘Within’.

The tests indicate that without technological spillovers, R&D levels do not

¹⁴Here, we do not make a distinction on the basis of whether contracts were actually chosen, as we did when analysing prices.

differ between the baseline and the contract treatment. 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. More specifically, R&D levels are found to be higher in the contract treatment than in the baseline treatment. Furthermore, within the contract treatment, R&D levels are higher with contracts than without contracts. This indicates that with high spillovers subjects are more cooperative in the R&D stage when they commit to an R&D contract, since for $\beta = 1$ the cooperative R&D level is above the competitive R&D level.

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. 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. It has been found in the previous section that prices are predominantly not at the Nash or cooperative level, which is indicated by the degree of price collusion (indicated by P) lying somewhere between 0 and 1, and not being equal to 0 or 1, at least not for all treatments. 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 behaviour 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 problem in the second, i.e. the pricing, stage. More specifically, 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 ϕ of the profit of the com-

petitor. Total profit to be maximized is then equal to $\pi_i + \phi\pi_j$ for $i, j = 1, 2$ and $i \neq j$. If ϕ is equal to 0, individual profit maximization results in the pricing stage and if ϕ is equal to 1, price collusion results. For any value of ϕ 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 ϕ and P (see appendix D),

$$P = \frac{2\phi(b - c)}{2b - c(\phi + 1)}, \quad (9)$$

where for any value of ϕ between 0 and 1, P is increasing and convex in ϕ . Since it is possible to establish theoretical R&D benchmarks for R&D competition and R&D cooperation as a function of ϕ , 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 2 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 in the last ten periods (see table 8) are located in the graphs in the form of grey zones. Each of the zones combines the average degree of price collusion in the last ten periods on the horizontal axis (\bar{P}_{26-35} in table 3), with the average R&D decision in that treatment, on the vertical axis.

The location of the average R&D decisions that represent R&D in the baseline treatment without spillovers and R&D in the contract treatment without spillovers in periods without R&D contracts (represented by *BASE* and *CON0* respectively in figure 2) suggests that R&D decisions in those treatments are very close to the SPN prediction. In the contract treatment without spillovers, average R&D in periods with R&D contracts (*CON1* in figure 2) is somewhat below the competitive level.

In the baseline treatment with spillovers and in the contract treatment without R&D contracts, the average R&D decision is located close to the curve representing R&D cooperation. Further, contracted R&D decisions in the contract treatment with spillovers definitely overshoot the cooperative level. The overshooting of contracted R&D could indicate that contracts were used to signal a willingness to collude in prices and could thus provide evidence for forward induction. With complete spillovers, strategic interactions in the R&D stage are similar to strategic interactions in the pricing stage. R&D decisions are also strategic complements then. To contract relatively high R&D decisions as a means to signal willingness to cooperate, is less risky than choosing high prices (cfr. relative profit changes resulting from

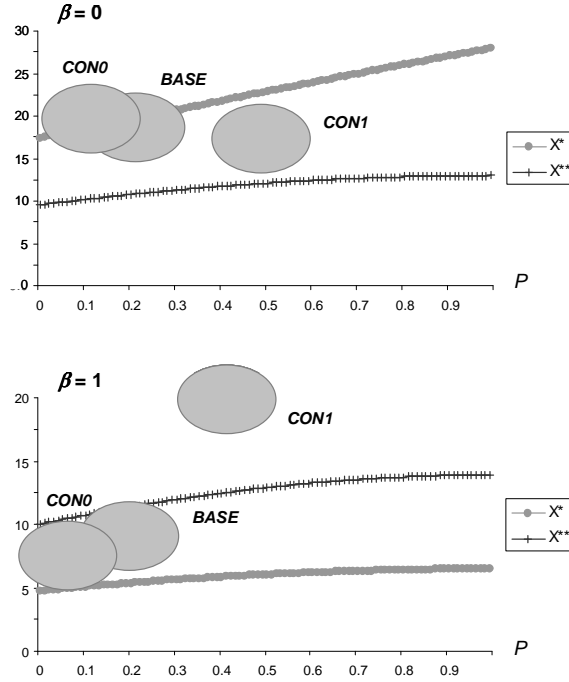


Figure 2: Simulations of competitive and cooperative R&D

changes in R&D decisions are smaller than those resulting from changes in prices).

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 between the competitive and the cooperative one are chosen in periods where the contract possibilities are used. With technological spillovers, R&D is close to the cooperative level if no R&D contracts could be made and if they could be, but were not made. Contracted R&D overshoots the cooperative level.

4.3 Welfare

Finally, we compare total welfare, i.e. the sum of consumer and producer surplus, between and within 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

$$W = U(q_1, q_2) - (\alpha - (x_1 + \beta x_2))q_1 - \delta \frac{x_1^2}{2} - (\alpha - (x_2 + \beta x_1))q_2 - \delta \frac{x_2^2}{2}. \quad (10)$$

Treatment	W_{1-35}	W_{26-35}	W_{5th}	W_{35}
$\beta = 0$				
<i>BASE</i>	4563.2 (316.8)	4499.5 (415.4)	4594.3 (312.5)	4680.4 (270.6)
<i>CON</i>	4390.8 (330.9)	4364.8 (422.2)	4535.6 (338.8)	4566.6 (350.5)
<i>CON0</i>	4646.2 (199.9)	4724.6 (137.6)	4686.0 (223.2)	4791.9 (94.3)
<i>CON1</i>	4269.9 (333.7)	4209.9 (419.0)	4373.7 (374.0)	4431.5 (381.6)
$\beta = 1$				
<i>BASE</i>	4758.0 (313.9)	4666.1 (291.9)	4797.9 (313.5)	4715.1 (281.7)
<i>CON</i>	4892.9 (374.6)	4790.4 (353.7)	4967.1 (394.6)	5176.4 (400.1)
<i>CON0</i>	4904.3 (368.3)	4778.1 (374.6)	4921.5 (369.9)	4571.7 (76.0)
<i>CON1</i>	4886.0 (391.0)	4900.8 (453.3)	4994.4 (418.9)	5269.5 (340.5)

Table 10: Average welfare and standard deviations

In table 10 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 baseline treatment than in the contract treatment. Also, within the contract treatment, welfare in periods without R&D contracts 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 not lower 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 11 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 the tables in the R&D section. ‘Between’ again refers to tests between the baseline and contract treatment and ‘Within’ to tests within the contract treatments. Differences in welfare between the baseline and contract treatments are mostly not statistically significant. Only in period 35, welfare in the contract treatment is significantly higher than in the baseline treatment, which is not surprising given that prices in the final period are lower in the contract treatment (see table 2) and that R&D in the contract treatment is higher than in the baseline treatment.

Further, the within-tests confirm that without technological spillovers, welfare in periods with R&D contracts is lower than welfare in periods without R&D contracts. The significance disappears in the last ten periods. With technological spillovers, differences in welfare within the treatments are not

	Between		Within	
	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$
<i>Periods 1-35</i>				
sig. (2-tailed)	0.105 ^a	0.551 ^b	0.003 ^c	0.441 ^d
N	31	26	11	9
<i>Periods 26-35</i>				
sig. (2-tailed)	0.167 ^a	0.337 ^b	0.109 ^c	0.075 ^d
N	31	26	3	6
<i>Final periods of groups of 5 periods</i>				
sig. (2-tailed)	0.206 ^a	0.264 ^b	0.003 ^c	0.021 ^d
N	31	26	11	9
<i>Period 35</i>				
sig. (2-tailed)	0.343 ^a	0.005 ^b	-	-
N	31	26	-	-
^a $H_1 : W_{CON} < W_{BASE}$; ^b $H_1 : W_{CON} > W_{BASE}$.				
^c $H_1 : W_{CON1} < W_{CON0}$; ^d $H_1 : W_{CON1} > W_{CON0}$.				

Table 11: Effects of contracts on welfare: non-parametric test results

statistically significant at the 5% level, when considering all or the last ten periods. When considering the final periods of all cycles of five periods, we find a significantly higher welfare level in periods with contracts. Again, the combination of high contracted R&D and low prices yields a high level of welfare.

Without spillovers, the relation between the degree of price collusion and welfare is similar to the relation between (absolute) prices and welfare, given that R&D decisions are similar in the baseline and contract treatment. That is, a higher degree of price collusion yields lower welfare. With spillovers, the relation between the degree of price collusion and welfare is not that straightforward since contracted R&D has been found to be significantly higher than other R&D decisions, which changes the theoretical benchmark prices.

5 Conclusion

In the paper we examined whether in experimental duopoly markets, cooperation in R&D facilitates price collusion. Subjects in the experiment were asked to repeatedly make R&D decisions and price decisions. For two scenarios of technological spillovers, i.e. no spillovers ($\beta = 0$) and complete spillovers ($\beta = 1$), a treatment without binding R&D contract possibilities and a treatment with contract possibilities were run.

Given that the experiment consisted of (a repetition) of two stages, there were some factors that complicated the data analysis. First, theoretical benchmarks of prices are formulated in terms of first-stage R&D decisions. Therefore, experimental R&D decisions had to be taken into account when analysing experimental prices. Second, theoretical benchmarks of R&D investment are based on the mode of product market competition, which is either price competition (individual profit maximization) or price collusion (joint profit maximization). So also with respect to the analysis of R&D decisions, actual pricing behaviour had to be taken into account.

We find that, overall, the degree of cooperation in the pricing stage in the contract treatments is higher than in the baseline treatments, implying that prices in the contract treatments deviate more from the subgame perfect Nash prediction than in the baseline treatments. Within the contract treatments a higher degree of price cooperation is only sustained when R&D contracts are actually committed to, and not otherwise. When subjects fail to agree on an R&D level, the subgame perfect Nash prediction generally performs well in predicting price decisions. Failing to sign an R&D contract might even yield a lower degree of cooperation than in baseline treatments, where subjects have no possibilities to engage in R&D contracts. This suggests that subjects ‘punish’ their counterparts, and necessarily also themselves, for failing to agree on R&D by choosing even lower prices than they ‘normally’ would (cfr. baseline treatments).

It is not unlikely that the finding that higher prices are sustained when R&D contracts are committed to, hinges on the repetition of the two-stage R&D and pricing game. Indeed, in the final period of the experiment the difference in degree of price collusion between baseline and contract treatments becomes statistically insignificant. Given that the aim of the experiment is to bring the static model a few steps closer to behaviour in the real world, rather than to test whether the static predictions are valid at each period of interaction, this should not be a worry. In the real world, firms repeatedly have new opportunities to engage in cooperative R&D projects, with the same or different partners, and repeatedly interact in the product market. And besides, we do find strong evidence for the effect of R&D contracts to be lasting, since within-differences of prices in the final periods of the five-periods cycles are statistically significant.

Laboratory R&D decisions are not as parallel as the degree of price collusion for both spillover scenarios. Without technological spillovers, R&D in the baseline treatment and in the contract treatment in periods where no contracts were committed to, is very close to the subgame perfect Nash level. Contracted R&D lies between the subgame perfect Nash and the cooperative level. With technological spillovers, non-contracted R&D decisions (in

the baseline and the contract treatment) are between the individual and the joint profit maximizing level. Contracted R&D overshoots the joint profit maximizing level which might be an indication of forward induction whereby the overshooting in R&D is used to signal a willingness to collude in prices. Finally, with spillovers more R&D contracts are committed to than without spillovers.

For anti-trust authorities that have recently been lenient 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 may carry over to the product market and as such create an environment where prices higher than the subgame perfect Nash level, or higher than they would be when there would be no possibilities to engage in cooperative R&D projects, may be sustained. Social welfare may be decreased by this.

Appendix A: Translated instructions¹⁵

You are participating in an economic experiment on decision making of producers. During this session you will be asked to make a number of decisions. The amount of your earnings depends on your decisions and decisions of another participant. The instructions are simple. If you carefully follow them and take good decisions, the probability of earning more money is larger. During the experiment you are not allowed to communicate with other participants.

In the experiment, the economy is divided into a number of industries. In each of these industries two sellers-producers are active who sell and produce similar products. Each of you represents a seller-producer in a specific industry. The other producer in your industry (henceforth your competitor) is in the same situation with the same conditions as you. Each producer, including you, has to take an investment decision first and then a price decision. The customers who eventually buy your products are simulated by the computer. The rule is: the higher the price of a certain variation of a product compared to another variation, the less products are bought of the first variation and the more of the other variation.

What you will earn, depends on your and your competitor's investment and price decisions. Under the title 'Profit simulation' you always have the possibility to calculate your and your competitor's profit. If you fill in hypothetical values of your own and your competitor's investment, and of your own and your competitor's prices, you can calculate your and your competitor's hypothetical profit by clicking the button 'Calculate'. By using this profit simulator you cannot enter your final investment or price decision, it only helps you to make your decisions.

Your investment decreases your and your competitor's unit production cost (with the amount of the investment) on the one hand and presents a cost equal to the square of the amount of investment. Your final investment decision should be filled in under the title 'Enter investment decision'. Each time you made an investment decision, it will remain constant for 5 subsequent periods. You have 200 seconds to take each investment decision. The investment should be between 0,0 and 50,0.

In the investment stages you have the possibility to engage in a contract with your competitor under the title called 'Contracts'. You can send her/him a proposal to both invest a certain amount (fill in the proposal in

¹⁵Note that we have only included instructions of the treatment with contract possibilities and complete technological spillovers. Instructions for the other treatments were the same, except for the paragraphs/sentences that refer to the contract possibilities and spillovers mode respectively.

the appropriate space and send it by clicking on ‘Send contract proposal’) and he/she can also send proposals. From the moment you sent a contract proposal, you are bound to invest what you proposed, if your competitor has agreed with your proposal. Your own and your competitor’s proposals are shown on the screen. You can accept a proposal of your competitor by selecting it and clicking on the button called ‘Accept this contract’. If a contract is committed to, you (and your competitor) are obliged to invest the contracted amount. You can find the number of the chosen contract on your screen.

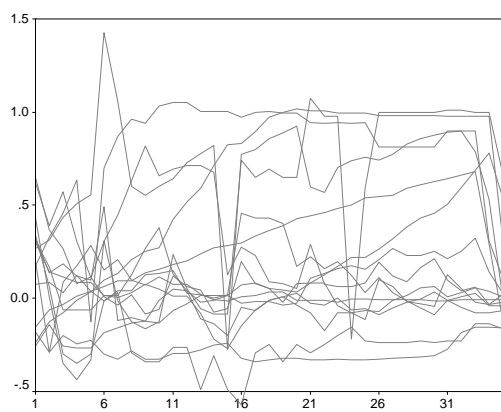
When all investment decisions are made, a second screen shows up, where you again have the possibility to calculate your and your competitor’s profit on the basis of hypothetical decisions (‘Profit simulation’). Information on your and your competitor’s investment decision in that period is given on your screen. In this second stage, you have to decide on the selling price of your products. Under ‘Profit simulation’ you can e.g. fill in the investment decisions in that period, and hypothetical prices, as to calculate the corresponding profit. Your final price decision should be given in under the title ‘Enter price decision’. You have 100 seconds take each price decision. The price should be between 0,0 and 245,0.

When all price decisions are made, a screen shows up with information on the decisions made in that period by you and your competitor. Information on the profit earned in that period is also shown. You can continue by clicking on ‘Continue to the following period’.

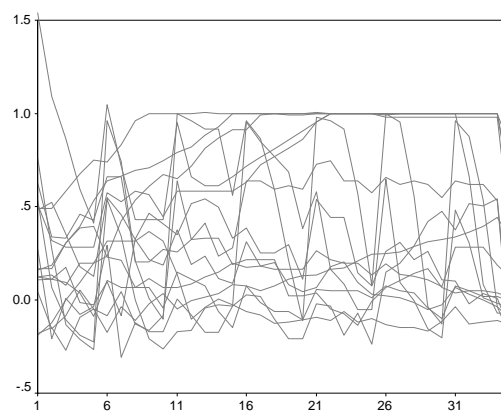
As already mentioned, your investment decision remains constant during 5 subsequent periods. In the periods without investment decisions, only price decisions are to be taken. Information of the previous or the same period is always shown on the screen.

The experiment contains 40 periods which implies that eventually 8 investment and 40 price decisions will have been taken. The first 5 periods are practice periods and do not influence your final earnings. Your final earnings in Euro are calculated by dividing the total profit you made in the experiment (from period 6 to 40) by 1500. The experiment will take about 2 hours.

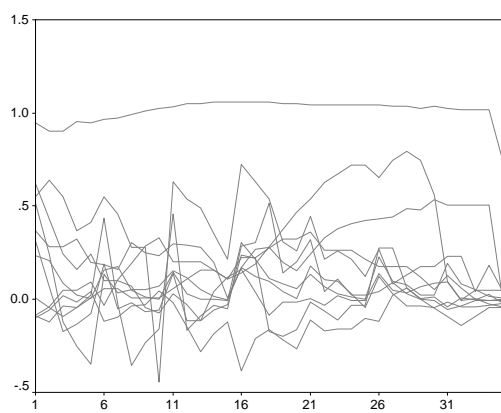
Appendix B: Transformed duopoly prices



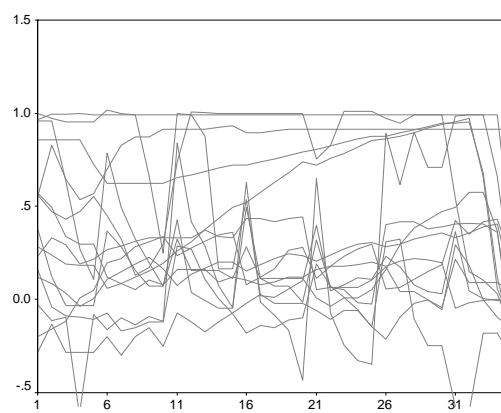
$\beta=0, \text{BASE}$



$\beta=0, \text{CON}$



$\beta=1, \text{BASE}$



$\beta=1, \text{CON}$

Appendix C: Average degree of price collusion by duopoly

	Without spillovers ($\beta = 0$)								With spillovers ($\beta = 1$)											
	P ₁₋₃₅	stdev	n	P ₂₆₋₃₅	stdev	n	P _{5th}	stdev	n	P ₃₅	P ₁₋₃₅	stdev	n	P ₂₆₋₃₅	stdev	n	P _{5th}	stdev	n	P ₃₅
Baseline treatments (BASE)																				
1	0.03	0.09	35	-0.01	0.00	10	0.05	0.11	7	-0.01	0.29	0.28	35	0.37	0.35	10	0.33	0.26	7	0.05
2	0.69	0.22	35	0.72	0.28	10	0.64	0.30	7	0.11	-0.09	0.11	35	-0.01	0.05	10	-0.06	0.11	7	-0.02
3	0.31	0.24	35	0.51	0.25	10	0.28	0.27	7	-0.12	0.04	0.14	35	-0.01	0.05	10	-0.05	0.13	7	-0.02
4	0.01	0.12	35	0.02	0.04	10	0.01	0.18	7	0.01	0.02	0.10	35	0.04	0.06	10	0.00	0.07	7	-0.04
5	0.64	0.42	35	0.91	0.21	10	0.63	0.41	7	0.32	0.02	0.17	35	0.01	0.04	10	0.01	0.11	7	0.00
6	0.12	0.29	35	0.50	0.16	10	0.12	0.30	7	0.54	0.08	0.08	35	0.08	0.08	10	0.01	0.02	7	0.01
7	0.83	0.25	35	0.72	0.27	10	0.80	0.40	7	0.00	0.12	0.12	35	0.09	0.08	10	0.10	0.13	7	-0.01
8	0.10	0.13	35	0.21	0.08	10	0.07	0.10	7	0.03	1.01	0.06	35	1.00	0.09	10	0.99	0.11	7	0.74
9	0.47	0.51	35	0.97	0.11	10	0.34	0.51	7	0.67	0.04	0.18	35	0.02	0.15	10	-0.02	0.13	7	-0.04
10	0.29	0.26	35	0.10	0.08	10	0.18	0.22	7	0.02	0.31	0.14	35	0.44	0.16	10	0.22	0.20	7	0.00
11	0.06	0.14	35	0.02	0.06	10	-0.01	0.08	7	-0.02	0.34	0.19	35	0.16	0.08	10	0.20	0.13	7	0.04
12	-0.28	0.06	35	-0.25	0.08	10	-0.27	0.07	7	-0.16										
13	-0.01	0.10	35	-0.02	0.04	10	-0.02	0.12	7	-0.04										
14	-0.23	0.16	35	-0.21	0.04	10	-0.29	0.11	7	-0.16										
15	0.09	0.15	35	-0.03	0.06	10	0.03	0.10	7	-0.07										
Contract treatments: periods without contracts (CON0)																				
1	-0.06	0.08	10			0	-0.06	0.03	2				0			0				
2			0			0			0		-0.01	0.02	5	-0.01	0.02	5	0.00		1	0.00
3			0			0			0		0.07	0.14	15	0.11	0.06	5	0.17	0.12	3	
4	0.02	0.31	5			0	-0.22		1		0.02	0.04	5			0	-0.03		1	
5	0.00	0.16	5			0	0.20		1				0			0			0	
6	0.16	0.06	10	0.13	0.04	5	0.12	0.06	2		-0.09	0.08	20	-0.08	0.08	5	-0.10	0.03	4	
7	0.12	0.17	10	-0.01	0.10	5	-0.03	0.20	2	-0.18			0			0			0	
8	0.66	0.38	10			0	0.77	0.33	2		0.04	0.13	10			0	0.01	0.06	2	
9	0.18	0.35	30	0.11	0.28	10	-0.03	0.23	6	-0.04			0			0			0	
10	-0.11	0.03	15	-0.14	0.02	5	-0.11	0.01	3		0.06	0.15	10	0.04	0.08	5	-0.05	0.00	2	
11	0.34	0.10	5			0	0.28		1				0			0			0	
12	0.19	0.20	35	0.07	0.06	10	0.14	0.17	7	-0.01	0.10	0.07	10	0.11	0.09	5	0.07	0.05	2	
13	0.04	0.25	35	0.32	0.24	10	-0.06	0.25	7	-0.24			0			0			0	
14	0.02	0.07	25	0.03	0.06	10	-0.07	0.07	5	0.01	-0.15	0.17	10			0	-0.10	0.03	2	
15	0.11	0.12	35	-0.01	0.05	10	0.09	0.16	7	-0.11	-0.28	0.14	15	-0.37	0.20	5	-0.28	0.03	3	-0.30
16	0.02	0.13	25			0	0.09	0.11	5											
Contract treatments: periods with contracts (CON1)																				
1	0.54	0.22	25	0.52	0.29	10	0.34	0.38	5	-0.31	0.50	0.33	35	0.70	0.40	10	0.47	0.40	7	-0.12
2	0.82	0.21	35	0.96	0.14	10	0.71	0.26	7	0.56	0.19	0.12	30	0.20	0.02	5	0.17	0.08	6	
3	0.92	0.15	35	0.98	0.06	10	0.94	0.11	7	0.80	0.29	0.08	20	0.37	0.09	5	0.30	0.06	4	0.22
4	0.56	0.44	30	0.45	0.50	10	0.01	0.29	6	-0.22	0.34	0.11	30	0.35	0.16	10	0.26	0.20	6	-0.12
5	0.76	0.33	30	0.66	0.48	10	0.75	0.42	6	-0.07	0.74	0.22	35	0.71	0.41	10	0.64	0.39	7	-0.20
6	0.26	0.13	25	0.23	0.08	5	0.13	0.04	5	0.12	0.06	0.16	15	0.04	0.19	5	-0.13	0.04	3	-0.16
7	0.26	0.19	25	0.23	0.08	5	0.18	0.18	5		0.95	0.16	35	0.87	0.29	10	0.86	0.37	7	0.08
8	0.90	0.14	25	0.96	0.12	10	0.87	0.18	5	0.61	0.25	0.18	25	0.36	0.23	10	0.12	0.23	5	-0.18
9	0.09	0.43	5			0	-0.27		1		0.68	0.37	35	0.55	0.48	10	0.67	0.46	7	-0.17
10	0.09	0.17	20	-0.11	0.04	5	0.09	0.21	4	-0.14	0.27	0.29	25	0.11	0.06	5	0.06	0.05	5	0.05
11	0.78	0.21	30	0.91	0.21	10	0.70	0.29	6	0.30	0.21	0.11	35	0.32	0.09	10	0.19	0.12	7	0.10
12			0			0			0		0.53	0.44	25	0.08	0.16	5	0.30	0.40	5	-0.01
13			0			0			0		0.86	0.11	35	0.91	0.00	10	0.87	0.13	7	0.91
14	0.05	0.07	10			0	-0.07	0.03	2		0.36	0.50	25	0.81	0.22	10	0.04	0.48	5	0.33
15			0			0			0		-0.05	0.14	20	0.01	0.29	5	-0.12	0.10	4	
16	0.33	0.06	10	0.33	0.06	10	0.32	0.00	2	0.32										

Appendix D: The ‘coefficient of cooperation’ approach

In the ‘coefficient of cooperation’ approach, a firm maximizes its own profit and a part ϕ 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 SPN 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 degree of price collusion of firm i P_i as follows,

$$P_i = \frac{p_i - p_i^{Nash}}{p_i^{Collude} - p_i^{Nash}}. \quad (11)$$

Note that at this step prices need not necessarily be symmetric. The index i in equation 11 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 ϕ for $0 < \phi < 1$.

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