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Publication date:
2003

[Link to publication in Tilburg University Research Portal](#)

Citation for published version (APA):

Suetens, S. (2003). *A Duopoly Experiment on Cooperative and Noncooperative R&D*. (CentER Discussion Paper; Vol. 2003-77). Vakgroep CentER.

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No. 2003–77

**A DUOPOLY EXPERIMENT ON COOPERATIVE
AND NONCOOPERATIVE R&D**

By S. Suetens

August 2003

ISSN 0924-7815

A duopoly experiment on cooperative and noncooperative R&D

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July 2003

Abstract

In this paper an experimental environment to test theoretical predictions concerning R&D behavior of firms in duopoly with allowance for R&D spillovers is created. The design and hypotheses of the experiment are based on the well-known model of d'Aspremont and Jacquemin in which R&D behavior of firms either competing or cooperating in R&D, is calculated. No difference in behavior between different spillover levels is found. Further, I find that — irrespective of the technological spillover level — subjects do not always commit to an R&D contract but if they commit to an R&D level in a binding contract, cooperative R&D levels are chosen. When subjects do not or cannot commit to a contract, the subgame perfect Nash equilibrium performs well in predicting R&D decisions.

JEL codes: C90, L13, O31

Keywords: R&D, duopoly, experiment

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1 Introduction

In the last decade an abundance of theoretical papers modelling competition and cooperation in R&D activities with technological spillovers have arisen. Most of these are extensions or modifications of the seminal paper of d'Aspremont and Jacquemin (1988)¹ (henceforth AJ), in which firms in duopoly decide on R&D in a first stage and on production quantity in a second stage. R&D in the models is to be interpreted as process R&D as it reduces unit production cost. Spillovers are usually modelled in a way that R&D efforts of one firm result in a decline of unit production cost of the other firm, without the latter bearing any cost. A general finding is that R&D investment under joint profit maximization (R&D cooperation) is higher than under individual profit maximization (R&D competition) if the spillover is above a certain threshold, and lower otherwise. The results are often interpreted as a rationale for government stimulation of the formation of research joint ventures in industries with large knowledge spillovers.

An empirical investigation of the effects of spillovers on R&D cooperation of Belgian firms has been carried out by Cassiman and Veugelers (2002). The authors distinguish between incoming flows and outgoing flows (appropriability) of knowledge or technological information and between different kinds of partners, of which about 10% are horizontally related competitors. They find that the probability of firms cooperating in R&D is higher when incoming spillovers and appropriability are high and conclude that their results are in conflict with most of the AJ like theoretical models, which predict that cooperative R&D incentives of firms increase with the level of (incoming and outgoing) spillover. Since in AJ like models, partners are horizontally related competitors and spillovers usually are symmetric², it is quite hard to compare these empirical findings with the theoretical ones. In fact, it is hard in general to empirically test the models' predictions. Spillovers, e.g. are difficult to measure empirically and can arise through different channels, such as e.g. the movement of R&D personnel, networks, meetings, patent applications and reverse engineering (see Veugelers, 1998). Therefore, I set up an experiment in this paper to investigate whether in an R&D game cooperative R&D outcomes are equally likely to be reached when spillovers are high compared to when they are low. An important advantage of the experimental approach is that the characteristics of spillovers and other assumptions made

¹Kamien et al. (1992); Poyago-Theotoky (1995); Leahy and Neary (1997); Petit and Tolwinski (1999); Hinlopen (2000)

²Examples of studies assuming asymmetries in e.g. costs or spillovers are Petit and Tolwinski (1999) and Amir and Wooders (2000).

in the models are completely under control. As such it is possible to identify unambiguously the extent of R&D cooperation under different spillover levels. As to distinguish between behavior of subjects when R&D contracts are allowed to be made and behavior in a noncooperative R&D game, I allow for binding contract possibilities in half of the treatments. Results indicate that in the noncooperative R&D game, R&D levels converge to the Nash prediction, either with or without technological spillovers. Further, contract possibilities in the contract treatments are not always used, but when they are used, cooperative R&D levels are contracted. When contract are not committed to, behavior is well predicated by Nash R&D equilibria. These results apply for both spillover levels.

So far the use of experimental methods to examine hypotheses about R&D behavior of firms is not so common. Examples of experiments on patent races are Hey and Reynolds (1991) and Sbriglia and Hey (1994). Another series of R&D experiments are found in Isaac and Reynolds (1986, 1988, 1992). These papers build on a stochastic invention model of innovation, in which the probability of producing a practically relevant innovation depends on the amount of R&D investment of a firm. Appropriability is introduced by inducing a distribution of payoffs among the sellers in the experimental markets. In the earliest experiments, this payoff distribution was exogenously determined by the experimenters, while in the most recent experiment it depended on price and production decisions of the sellers. Main conclusions are that firms over-invest in R&D relative to the social optimum in a Nash equilibrium if private rewards from R&D equal social rewards and that a reduction in appropriability for the innovator leads to reduced R&D spending by all participants. They also find that risk-neutral noncooperative Nash equilibrium predictors perform relatively well. Next to this, the experimental results give support to behavior that is defined as Schumpeterian competition, which is characterized by falling prices as a result of the cost-reducing innovations and by non-creative firms being competed away. The theoretical difference from a socially optimal viewpoint between monopoly and oligopoly markets has also been found in their experiments. Market prices tend to fall more slowly under monopoly than under oligopoly. A more recent example of an experimental paper on R&D is Jullien and Ruffieux (2001). In their experiments 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 also allow for spillovers but do not find any influence on R&D incentives. It is found that markets generally are efficient but that convergence of market prices towards their competitive level is slower in the presence of endogenous shocks, when all oligopolists gain a cost reduction

that shifts the aggregate supply curve downwards. Uncertainty would cause heterogeneity in behavior.

As such, none of the previous experimental papers on R&D consider the effects of contract possibilities and the comparison between a noncooperative and a cooperative R&D game. They neither address the link between spillovers and incentives to choose cooperative R&D levels. The paper is organized as follows. In section 2, the model on which the experiment is based, is resumed. In section 3, the hypotheses to be tested and the experimental design are gathered from the model. A descriptive and an econometric analysis of the experimental results are presented in section 4. Section 5 concludes.

2 The AJ model

AJ assume that perfectly informed firms in a duopoly simultaneously decide on R&D in a first stage and are engaged in Cournot competition in a second stage. In what follows, an industry with 2 symmetric firms is considered which are of equal size, have equal cost functions and produce a homogeneous good. The industry is characterized by a linear inverse demand function of the following form:

$$P(Q) = a - bQ \quad (1)$$

$$\begin{aligned} \text{with } & a, b > 0, \\ & Q = Q_i + Q_j, \\ & Q_i = \text{production quantity of firm } i. \end{aligned}$$

The unit cost function of firm i is assumed to be decreasing in its amount of ‘effective’ R&D, X_i , (Kamien et al., 1992) which is composed of its own R&D, x_i , and spilled over R&D of firm j , βx_j . The spillover parameter is between 0 and 1 and determines how much firm i can take advantage of the other firm’s R&D expenditures without bearing any cost. Assuming a linear function yields the following expression for the unit cost of firm i :

$$c_i(X_i) = \alpha - \gamma X_i \quad \gamma > 0, \alpha < a. \quad (2)$$

R&D investments are assumed to have decreasing returns, which is imple-

mented in the model as a quadratic R&D cost function³:

$$f_i(x_i) = \delta \frac{x_i^2}{2} \quad \delta > 0. \quad (3)$$

The game is as usually solved using backward induction. As Cournot competition is assumed, in the second stage firms individually maximize their profit with respect to their production quantity. Maximizing profit of firm i , $\pi_i = P(Q)Q_i - c_i(X_i)Q_i - f_i(x_i)$, for $i = 1, 2$ and replacing production quantities by their maximizing values yields the following first-stage profit function:

$$\pi_i^e = \frac{(a - \alpha + 2\gamma(x_i + \beta x_j) - \gamma(x_j + \beta x_i))^2}{9b} - \delta \frac{x_i^2}{2} \quad \forall i = 1, 2; j \neq i. \quad (4)$$

Suppose further that in the first stage firms play a noncooperative R&D game. If both firms choose to maximize their own profit and expect the same behavior from their competitor, the first-stage maximization problem is $\max_{x_i} \pi_i^e, x_i > 0$, for $i = 1, 2$, and leads to the following (symmetric) equilibrium R&D level⁴:

$$x^* = \frac{2\gamma(a - \alpha)(2 - \beta)}{9b\delta - 2\gamma^2(1 + \beta)(2 - \beta)} \quad \forall i = 1, 2. \quad (5)$$

If firms coordinate their R&D activities as to maximize the sum of their profits⁵ the symmetric maximization problem $\max_{x_i} \sum_{i=1}^2 \pi_i^e, x_i > 0$, should be solved for $i = 1, 2$, which results in the following unique outcome for R&D⁶:

$$x^{**} = \frac{2\gamma(a - \alpha)(1 + \beta)}{9b\delta - 2\gamma^2(1 + \beta)^2} \quad \forall i = 1, 2. \quad (6)$$

Symmetric profits calculated in the competitive and the cooperative outcomes are respectively

$$\begin{aligned} \pi^* &= \frac{\delta(a - \alpha)^2(9b\delta - 2\gamma^2(2 - \beta)^2)}{(9b\delta - 2\gamma^2(1 + \beta)(2 - \beta))^2} \\ \text{and} \quad \pi^{**} &= \frac{\delta(a - \alpha)^2}{9b\delta - 2\gamma^2(1 + \beta)^2}. \end{aligned}$$

³In Amir (2000) a model with decreasing returns to own R&D — i.e. the AJ model — is compared with one with decreasing returns to effective R&D. In the latter case, instead of defining unit cost as a linear function of effective R&D and R&D cost as a quadratic function of R&D, unit costs are a square root function of R&D and R&D cost is the decision variable.

⁴The second-order condition is $9b\delta > 2\gamma^2(2 - \beta)^2$.

⁵In Kamien et al. (1992) this form of R&D cooperation is called cartelization.

⁶The second-order condition is $9b\delta > 2\gamma^2(5\beta^2 - 8\beta + 5)$.

π^{**} is larger than π^* if the spillover is not equal to 0.5 (see also Kamien et al., 1992; Hinloopen, 2000). It is clear that the strategic interactions in the non-cooperative one-shot R&D game have some properties of a prisoners' dilemma, such as e.g. Cournot games of output competition or Bertrand games of price competition. Although firms have incentives to cooperate in R&D, individual profit maximization (i.e. R&D competition) is the best response to any of the strategies of the competitor and thus represents the Nash equilibrium. In the cooperative game, joint profit maximization is the prediction, given that firms can credibly commit to the (symmetric) cooperative R&D level.

3 Experimental design and hypotheses

To focus on the R&D decisions made by the firms, in the experiment the quantity decision is controlled by setting production quantity at its Nash-Cournot equilibrium which is a function of firms' R&D expenditures. This is justified because European and American antitrust laws forbid firms to collude in the output market. Besides, in this way I avoid testing optimization in both stages (R&D and production) and backward induction. Thus, the experiment concentrates on the R&D stage that is nested in the more general two-stage game. The most widely separated levels of spillovers that are possible are used, i.e. complete versus no R&D spillovers, to sharpen possible contrasts in the results (Friedman and Sunder, 1994). The parameters of the demand function, of the R&D cost function and of the unit cost function are treated as constants. The chosen parameters are $a = 250$, $b = 5$, $\alpha = 100$, $\gamma = 2$ and $\delta = 5^7$ and correspond to the following R&D equilibria, with x^* and x^{**} representing the Nash prediction and the (symmetric) cooperative outcome respectively:

$$x^* = \begin{cases} 5.7 & : \beta = 0 \\ 2.9 & : \beta = 1 \end{cases}$$

and

$$x^{**} = \begin{cases} 2.8 & : \beta = 0 \\ 6.2 & : \beta = 1. \end{cases}$$

The experiment consisted of three computerized experimental sessions⁸ with 40 participants in total, recruited from undergraduate economics courses and

⁷The parameter values satisfy requirements of stability as proposed by Henriques (1990) and correspond to symmetric R&D solutions (see Salant and Shaffer, 1998).

⁸I used the software *z-Tree*, developed by Fischbacher (1999).

randomly divided into fixed groups of two (duopolies). The students were not informed about the identity of their competitor. Each of the sessions took less than 80 minutes. In the experiment subjects were told that they participated in an experiment on decision-making in firms. More specifically, the subjects were told that they were sellers in a market with two sellers of a non specified product. They had common knowledge about the fact that they were all subject to the same conditions related to demand and costs. The subjects had to make (non-specified) investment decisions in the interval of $[0, 25]$ ⁹ during 27 periods, which decreased their unit production cost — according to the linear unit cost function — and which induced a certain cost — calculated on the basis of the quadratic R&D cost function. This decision influenced profit also via equilibrium production quantities. In the complete spillovers case, subjects were told that their R&D decision also decreased unit production cost of the other producer in his/her market, without the latter bearing any cost. Subjects were able to simulate their production quantity, selling price, unit production cost, total R&D cost and profit on the basis of their own decision and the other producer's decision. Each period took around two minutes, except the first one which took longer to let subjects become acquainted with the instructions and the computer program. For participating and following the instructions carefully they received 100 Belgian francs (2.5 EUR). What they would earn on top of this was related to the sum of the profits they made in the experiments, which in turn depended on their own and their competitors' decisions. They were told that they would earn on average 400 Belgian francs (around 10 EUR).

Since the players' strategies stretch a continuum of possible strategies and are thus not limited to either individual or joint profit maximization, the noncooperative R&D game is not really a prisoners' dilemma, although the same conclusion on the equilibrium outcome is reached. The Nash equilibrium is the expected theoretical outcome and finitely repeating the prisoners' dilemma game does not change the Nash equilibrium. Thus, the first hypothesis would be the following.

Hypothesis 1 *If no binding contracts can be made, firms compete in R&D, irrespective of the level of technological spillovers.*

For both spillover levels I allowed for the possibility of committing to a contract in half of the duopolies. In these treatments subjects could propose binding contracts to their competitor and could accept contracts proposed

⁹This interval was necessary to obtain no-nonsense results for variables such as unit production cost.

by their competitor. As in d’Aspremont and Jacquemin (1988) symmetry is assumed with respect to the cooperative solutions, only symmetric contracts were allowed. Once subjects had proposed a contract they were committed to their proposal when the proposal was accepted. Thus there was no option to deviate from an accepted contract. I expect that firms use contracts and commit to the cooperative R&D level, as profit that corresponds to the cooperative level is higher than profit that corresponds to the Nash level. As such, the following is the second hypothesis.

Hypothesis 2 *If binding contracts can be made, firms commit to a contract and choose the cooperative R&D level, irrespective of the level of technological spillovers.*

As such, four treatments were run. That is ‘no contract’ and ‘contract’ for both technological spillover levels of 0 and 1. An equal number of subjects was appointed to each of the four treatments, i.e. 10. In what follows I often refer to the treatments as T_{kl} , where k refers to the spillover level and l to a dummy that is equal to 0 (1) for treatments without (with) contract possibilities.

4 Experimental results

When analyzing the experimental results I am confronted with the possibility that duopolists are influenced by their competitor’s behavior in making their R&D decisions, such that observations on R&D decisions are not independent within the duopolies. Using the sum of R&D decisions by duopoly, circumvents this problem and creates independent observations per duopoly. Furthermore, assuming symmetry between competitors makes sense, since Wilcoxon signed ranks tests yielded no significant differences in average R&D decisions between competitors within duopolies¹⁰. That is why in the analyses the sum of R&D decisions by duopoly, referred to by capital X , is used. If period 0 is ignored, for each subject I have a time series of 26 periods. As the theoretical equilibria are symmetric, equilibria in each duopoly are twice the individual equilibrium (see table 1 for the theoretical duopoly benchmarks). In what follows a distinction is made between the descriptive and statistical analysis and the econometric analysis. In a last subsection I focus on contracting behavior of subjects.

¹⁰Averages over all periods, over the first ten and the last ten periods have been compared for this purpose.

Figure 1: Boxplot

4.1 Descriptive and statistical analysis

In figure 1 box plots of averages of the duopoly R&D decisions over all 26 periods are presented, as to get a first idea of how the data look like. Data of each of the four treatments are grouped. 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 deviate more than 3 box lengths from the upper and lower edge of the box. One duopoly in the treatment with $\beta = 0$ and without chat or contract possibilities is identified as an outlier (marked with a star).

It is observed that in the no-spillover treatment without contract possibilities, the median of the average duopoly R&D decisions is quite close to the Nash equilibrium prediction. The average R&D decision of the outlying duopoly is at the cooperative level though. In the complete spillover treatments the median of R&D decisions in the treatment without contract possibilities lies closer to the Nash prediction than to the cooperative R&D level, but not as close as in the treatment without spillovers. In the contract treatments the median R&D levels are somewhere between the Nash and the cooperative level for both spillover levels. On the other hand, with spillovers, median R&D is higher in the contract treatment than in the treatment without contract possibilities and without spillovers median R&D is lower in the contract treatment compared to the baseline treatment. From the previous

section we know that without spillovers, the cooperative R&D level is lower than the competitive level, while with spillovers, cooperative R&D is higher than competitive R&D. Thus, the box plots point in the direction that either with or without spillovers, subjects tend to cooperate more in the contract treatments than in the baseline treatments.

The data in the box plots are based on averages taken over all periods. Since subjects in the experiment had 26 periods to learn to play certain strategies, R&D decisions could differ between different sub-periods. In table 1 averages and standard deviations across duopolies of duopoly R&D decisions averaged over all periods and two sub-periods are presented. The two sub-periods are the first ten and the last ten periods respectively. The two theoretical benchmarks, i.e. the Nash and the cooperative R&D levels, are included in the table with one and two stars respectively. The first two rows in the table represent averages of the treatments without contract possibilities (T_{00} and T_{10}) and averages of the contract treatments (T_{01} and T_{11}) respectively, for both spillover levels. In the last two rows, I made a distinction within the contract treatment between R&D decisions in periods in which contracts were not committed to and contracted R&D decisions. T_{010} and T_{110} refer to average R&D decisions in periods without contracts for $\beta = 0$ and $\beta = 1$, while T_{011} and T_{111} refer to average contracted R&D decisions.

Average R&D decisions in the baseline treatments are clearly very close to the Nash R&D levels for both spillover levels. With full spillovers, average R&D in the first periods lies between both theoretical benchmarks, while in the ten last periods it is very close to the Nash equilibrium. Without spillovers, also in the first periods R&D decisions are close to the Nash level. Within the contract treatments, observed average R&D decisions in periods in which no contracts are signed, are very close to the Nash equilibria for both spillover scenarios. This is the case for averages taken over all and the last ten periods. In the first ten periods, R&D decisions are much closer to the cooperative level. For average contracted R&D decisions, observations are the opposite, i.e. they evolve from close to the Nash level to close to the cooperative level. This could indicate that subjects learned to contract cooperative R&D levels and to play Nash in periods in which no contracts were made.

As to investigate whether R&D decisions differ in a statistically significant way between treatments and within the contract treatments, I performed non-parametric tests. I compared average R&D decisions of the duopolies in the last ten periods in the contract treatments with the decisions in the treatments without contract possibilities. Only results of the last ten periods are reported because when all periods are taken into account, no statistically

	X^*	X^{**}	X_{1-26}	X_{1-10}	X_{17-26}
$\beta = 0$					
T_{00}	11.5	5.5	10.7 (2.94)	11.1 (3.51)	10.5 (2.79)
T_{01}	11.5	5.5	8.0 (1.72)	9.3 (1.67)	6.8 (0.74)
T_{010}	11.5	5.5	12.3 (1.40)	6.8 (2.55)	13.7 (1.30)
T_{011}	11.5	5.5	5.9 (0.15)	13.3 (4.06)	5.8 (0.10)
$\beta = 1$					
T_{10}	5.7	12.4	7.2 (1.95)	9.4 (2.84)	5.9 (2.59)
T_{11}	5.7	12.4	9.5 (1.08)	8.8 (3.03)	9.9 (1.22)
T_{110}	5.7	12.4	5.8 (1.60)	11.2 (1.79)	4.7 (1.42)
T_{111}	5.7	12.4	12.3 (0.62)	6.1 (0.51)	12.3 (0.11)

Table 1: Average R&D decisions and standard deviations

	Between		Within	
	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$
z	-1.567	-1.984	-1.826	-2.023
exact sig. (2-tailed)	0.151	0.056	0.126	0.062
exact sig. (1-tailed)	0.076	0.028	0.063	0.031

Table 2: Mann-Whitney and Wilcoxon signed ranks test results

significant differences are found. Furthermore, it is generally accepted that subjects usually learn to play equilibrium or other strategies and that their behavior only stabilizes and converges to a theoretical benchmark at the end of the experiment. Table 1 contains indications that this kind of learning or converging arises in our experiment. Indeed, average R&D decisions in the final ten periods are in general closer to one of the two theoretical benchmarks than in the beginning of the experiment. Results of the tests are under the header ‘Between’ in table 2. The null hypothesis is that R&D decisions without contract possibilities do not differ from R&D decisions with contract possibilities. On the basis of one-tailed tests I would conclude that with spillovers, R&D decisions are higher when contracts possibilities are available compared to when they are not with a 5% significance. Without spillovers, the conclusion would be the opposite with a 10% significance level, i.e. R&D decisions are lower when contract possibilities are available compared to when they are not available.

In another series of tests, of which results are reported in the same table under the header ‘Within’, I compared R&D decisions in the contract treatments averaged over periods in which contracts were not made with average contracted R&D decisions. The tests I used, are Wilcoxon signed ranks tests. Again, only observations in the last ten periods were used to compute aver-

ages. Results are very similar to those of the Mann-Whitney tests. Thus, for complete spillovers some evidence exists that R&D levels are higher if subjects commit to an R&D contract (with 5% significance). In the no-spillover treatment it is found that if R&D contracts are used, subjects do less R&D than if R&D is not contracted, with a significance of 10%. So in general, no different conclusions regarding R&D behavior are made for the scenarios with and without spillovers.

The above non-parametric tests are highly conservative and ignore important information about the dynamic structure of the data (Königstein, 2000). Indeed, for each duopoly a time series exists covering 26 periods of R&D investment decisions (without period 0). When simply taking averages of R&D decisions in some sub-period (in our case the last sub-period), the time series structure of the data is completely ignored. That is why in what follows I use econometric techniques to analyze the experimental data further.

4.2 Econometric analysis

To be able to compare the experimental R&D decisions with the theoretical competitive and cooperative equilibrium R&D decisions, it is necessary to estimate an equilibrium value of the experimental R&D decisions. For this purpose it is assumed that the R&D decision of each observation unit (duopoly) and in each period is equal to the sum of a static long-term equilibrium value, which is constant and thus not subject- nor time-specific, and a subject- and time-specific random or residual fluctuation. An econometric model that satisfies this assumption is the following model (Mason and Phillips, 1997):

$$X_{k,l,t} = \theta_k + u_{k,l,t} \quad (7)$$

where the sum of R&D decisions of the l th duopoly equals $X_{k,l,t}$ ¹¹. The index k represents the treatment, l the duopoly and t the time period. θ_k is to be interpreted as the long-term equilibrium R&D investment in treatment k and $u_{k,l,t}$ as the residual fluctuations of pair l 's R&D investment in period t around the long-term equilibrium in treatment k . Further it is expected that a subject's and as such a pair's R&D decisions are correlated with R&D decisions in previous periods, implying that the residuals in equation 7 follow an autoregressive process, such that

$$u_{k,l,t} = \sum_{j=1} \lambda_{kj} u_{k,l,t-j} + \epsilon_{k,l,t} \quad (8)$$

¹¹This capital X should not be confused with the expression X_i of section 3, which represented effective R&D of firm i .

with $\epsilon_{k,l,t}$ following a white noise process. The AR(j) series is stationary and thus converges if the roots of the characteristic equation lie outside the unit circle. For an AR(2) process this condition is reduced to $|\lambda_{k1}| < 1$, $|\lambda_{k2}| < 1$, $\lambda_{k1} + \lambda_{k2} < 1$ and $\lambda_{k2} - \lambda_{k1} < 1$ (Greene, 2000). Equations 7 and 8 are unified in the model

$$X_{k,l,t} = \lambda_{k0} + \sum_{j=1} \lambda_{kj} X_{k,l,t-j} + \epsilon_{k,l,t}, \quad (9)$$

with the same convergence or stability conditions as in 8. An estimate for the long-term equilibrium θ_k is computed from λ_{k0} as follows: $\theta_k = \lambda_{k0}/(1 - \sum_{j=1} \lambda_{kj})$.

For each of the four treatments I estimated a model as in (9) with the residuals of equation (7) following an AR(2) process. The choice of 2 lags in the autoregressive process is rather arbitrary, although with 2 lags one should in general be able to correct for possible autocorrelation problems without losing too many degrees of freedom. As in the non-parametric tests some statistical evidence has been found for differences in R&D decisions within the contract treatments in the sense that it mattered whether contract possibilities have actually been used by the subjects, a dummy is included in the econometric equations. This dummy is equal to one in periods in which a contract has been committed to, and equal to zero in periods in which no contracts have been made. As to allow for different slopes within the contract treatments, interactions between the dummy and the right-hand-side variables (i.e. the lagged R&D decisions) are also included. As it is assumed that all parameters are the same across the cross-sectional observation units (duopolies per treatment), it is likely that some cross-sectional correlation exists. Moreover, based on the inspection of the variances of the different duopoly decisions within the treatments, cross-sectional heteroskedasticity is also likely. Thus, feasible GLS is applied without imposing restrictions on cross-sectional heteroskedasticity and correlation. In table 3 the econometric results are given.

The superscripts 0 and 1 in the second part of the table refer to the parameter estimates not taking and taking into account the dummy respectively. The sums of $\hat{\lambda}_{ki}^0$ and $\hat{\lambda}_{ki}^1$ for $i = 0, 1, 2$ are used to compute the constant term and the slope when contract possibilities are actually used within the contract treatments, while when no contract possibilities are used, the constant term and the slopes are simply $\hat{\lambda}_{ki}^0$ for $i = 0, 1, 2$. Standard errors were estimated heteroskedastic-consistently, as tests indicated possible within-heteroskedasticity for some equations. The standard errors of the static long-run equilibria have been calculated according to corollary 4.2.2.

without contract possibilities				with contract possibilities					
	T_{00}		T_{10}			T_{01}		T_{11}	
$\hat{\lambda}_{k0}$	3.64	[.000]	1.77	[.000]	$\hat{\lambda}_{k0}^0$	12.39	[.000]	3.51	[.000]
$\hat{\lambda}_{k1}$	0.35	[.000]	0.47	[.000]	$\hat{\lambda}_{k1}^0$	0.06	[.169]	0.18	[.028]
$\hat{\lambda}_{k2}$	0.28	[.000]	0.20	[.000]	$\hat{\lambda}_{k2}^0$	-0.06	[.108]	0.20	[.074]
					$\hat{\lambda}_{k0}^1$	-6.85	[.000]	6.63	[.000]
					$\hat{\lambda}_{k1}^1$	0.08	[.117]	-0.12	[.010]
					$\hat{\lambda}_{k2}^1$	-0.04	[.302]	-0.09	[.177]
$\hat{\theta}_k$	9.86	(0.39)	5.36	(0.40)	$\hat{\theta}_k^0$	12.41	(0.42)	5.62	(0.44)
					$\hat{\theta}_k^1$	5.78	(0.08)	12.15	(0.05)
$GOF^{(a)}$	0.16		0.85		$GOF^{(a)}$	0.93		0.94	
Durbin-h ^(b)	1		2		Durbin-h ^(b)	1		1	
N*T	5*24		5*24		N*T	5*24		5*24	

P-values are in square brackets and standard errors in round brackets.

$\hat{\theta}_k$ without outlier in T_{00} is 11.94 (0.25) and GOF is 0.39.

(a) Greene (2000).

(b) Number of duopolies with autocorrelation with $\alpha = 0.05$.

Table 3: Econometric results

in Fomby et al. (1984). For each equation a Durbin-h-statistic has been calculated and the number of times the null hypothesis of no autocorrelation has been rejected, is put under the row header ‘Durbin-h’. The autocorrelation problems in some of the duopolies possibly are the consequence of restricting the parameter to be the same across duopolies in each treatment. From the table we learn that it is not always the case that the two lags of the dependent variable significantly differ from zero. We do keep the two lags though, as for final estimates to be comparable.

It further seems that the dummies are highly significant, which confirms that significant differences exist within the contract treatments between R&D levels in periods in which subjects have used the contract possibilities and in periods that subjects have not used them. Removing the outlier in the treatment ‘no spillover, no contract’ yielded estimates that are closer to Nash predictions, which was to be expected since the average outlying duopoly’s R&D decision is close to the cooperative level. The goodness-of-fit is in general higher in the contract treatments than in the other treatments. The variance of the dependent variable in the contract treatments, i.e. duopoly R&D decisions, is thus better explained by the model than in the no-contract treatments. This could be partly due to the smaller variance (see also table 1) of R&D decisions when the possibility to make a contract is available.

Further, the estimated static long-run R&D decisions ($\hat{\theta}_k$) are compared with the theoretical predictions in table 1 using t-tests as to test the hypotheses formulated in the previous section. Table 4 contains the results of these t-tests. The superscripts 0 and 1 in the table again refer to estimates without and estimates with the dummies that refer to whether a contract has actually been committed to. From the t-tests it can be concluded that R&D behavior of subjects with complete spillovers and no contract possibilities does not significantly differ from competitive Nash behavior. In the no-spillovers case, this conclusion can only be made when the outlier is ignored. In the contract treatment without spillovers, estimated long-run R&D levels differ from the Nash prediction and the cooperative outcome in a statistically significant way. The difference between the estimated R&D level when no contracts are signed and the Nash prediction is only significant at a level of 5% though. These highly significant differences result from the fact that the variances of the estimates are very small. E.g. a statistical comparison between the estimated R&D level without spillovers for cases that contracts are signed, which is 5.78 with a standard deviation of 0.08, and the cooperative R&D level without technological spillovers, which is 5.5, yields a significant difference according to the t-test. Since in terms of profit in experimental units, this would not yield a notable difference, we have to be cautious and to some extent conservative when interpreting the t-test results. The same remark is valid for the contract treatment with spillovers. The estimated R&D level based on cases in which a contract is chosen, is equal to 12.15 with a standard deviation of 0.05, while the cooperative R&D level is 12.4. For periods in which no contract is signed, no significant difference is found between the R&D estimate and the Nash prediction. Bringing the most and the least conservative analyses—the non-parametric tests and the t-test based on the econometric estimates respectively—together, I would conclude that irrespective of the spillover level, subjects choose the cooperative R&D level in periods where they commit to a contract and choose the competitive level otherwise.

To summarize, commitment to binding R&D contracts guarantees that R&D levels are cooperative, either with or without spillovers. When committing to an R&D contract is not possible, or simply not done, R&D behavior is competitive, irrespective of the level of spillovers. Thus, so far, hypothesis 1 is not rejected and no difference in R&D behavior of subjects between both spillover levels is found. As to gain more inside in the contracting behavior of the subjects, I focus on data of the contract treatments in the following subsection.

	spillover = 0		spillover = 1	
	T_{00}	T_{01}	T_{10}	T_{11}
$H_0: \theta_k^0 = X^*$	-4.16 ⁺⁺	2.19 ⁺	-0.96	-0.28
$H_0: \theta_k^0 = X^{**}$	11.03 ⁺⁺	16.26 ⁺⁺	-17.66 ⁺⁺	-15.54 ⁺⁺
$H_0: \theta_k^1 = X^*$	-	-75.87 ⁺⁺	-	122.08 ⁺⁺
$H_0: \theta_k^1 = X^{**}$	-	3.31 ⁺⁺	-	-5.62 ⁺⁺

Without the outlier, the t-values in T_{00} are respectively 1.87 and 26.10.

⁺⁺ H_0 is rejected with $\alpha = 0.01$ (critical t value is 2.63).

⁺ H_0 is rejected with $\alpha = 0.05$ (critical t value is 1.98).

Table 4: Results of t-tests

4.3 Contracts

The aim of this subsection is to analyze further how contracting behavior evolves during the experiment and how it differs between the two technological spillover levels. In table 5 percentages are given for all duopolies, of shares of periods in which contracts are proposed and committed to, in the total number of periods. In the first part of the table the percentages refer to the shares of periods in which contract proposals are made by at least one out of two subjects in a duopoly. In the second part of the table percentages of shares of contracts actually committed to, are given. In the columns of the table a distinction is made between the first ten and the last ten periods, as to investigate learning behavior of the subjects. The average shares across all duopolies are in the last rows of both parts of the table.

It is observed that more contracts are in general committed to when no technological spillovers are present than with spillovers. But since this difference is statistically not significant¹², I pay no further attention to it. For contract proposals, no such difference neither exists. I further observe that for both spillover levels more contracts are proposed and committed to in the last periods of the experiment than in the first periods. The difference between the amount of contracts actually committed to in the first ten periods and the amount in the last ten periods is found to be statistically significant with a p-value of 0.002¹³. This provides evidence for learning behavior of subjects. Subjects become acquainted with the contract possibility after some time and thus learn to commit to contracts. This conclusion also coincides with the observation that subjects learn to play theoretical strategies, which

¹²A Mann-Whitney test yields a p-value of 0.406 for the related two-tailed test for all periods and 0.107 for the last ten periods.

¹³This results from a two-tailed Wilcoxon signed ranks test.

duopoly	$\beta = 0$			$\beta = 1$		
	all	1-10	17-26	all	1-10	17-26
<i>Contract proposals</i>						
1	100%	100%	100%	85%	80%	80%
2	73%	30%	100%	81%	80%	80%
3	92%	90%	100%	100%	100%	100%
4	96%	90%	100%	89%	90%	100%
5	96%	100%	100%	100%	100%	100%
average %	92%	82%	100%	91%	90%	92%
<i>Contracts actually committed to</i>						
1	89%	90%	100%	50%	40%	60%
2	39%	0%	80%	32%	10%	50%
3	54%	40%	80%	58%	40%	80%
4	89%	80%	90%	46%	30%	70%
5	69%	40%	90%	89%	80%	90%
average %	69%	40%	88%	55%	50%	70%

Table 5: Percentages of contracts

is supported by the data in table 1. More specifically, especially in the last periods, contracted R&D decisions are close to the theoretical cooperative R&D level, while R&D decisions in periods where no contracts are made, are close to the (subgame perfect) Nash R&D level. With respect to contract proposals, a similar test on the difference between the amount of contract proposals at the beginning and at the end of the experiment gives none, or at least much less significance, i.e. a p-value of 0.125. Thus, it is unlikely that the increase in contracts made, can only be explained by an increase in the amount of contract proposals during the experiment.

It is found that during the experiment more and more contracts were made, but this does not imply that finally, subjects always commit to a contract. In the previous subsection, R&D behavior in periods in which no contracts are committed to, has already been found to converge towards R&D competition. Contracted R&D, on the other hand, converges towards the cooperative level. It remains to be examined what the reasons are that in some periods subjects did not commit to a contract. A first reason could be that no contract proposals were made in these periods. But, as table 5 shows, the percentages of periods in which contracts have been proposed is high and definitely higher than the percentage of periods with contracts for all duopolies and all (sub)periods (except duopoly 1 in the last ten periods)¹⁴. This implies that a significant amount of contract proposals was not accepted in either

¹⁴This conclusion can also be made based on Wilcoxon signed ranks tests.

duopoly	$\beta = 0$		$\beta = 1$	
	not accepted	accepted	not accepted	accepted
<i>Periods 1-26</i>				
1	2.99 (0.76)	2.80 (0.40)	8.41 (6.20)	6.22 (0.26)
2	3.93 (3.31)	2.95 (0.05)	5.62 (1.47)	6.49 (1.48)
3	3.44 (0.89)	2.99 (0.29)	5.62 (1.39)	5.70 (1.18)
4	2.49 (1.75)	2.97 (0.66)	6.90 (4.11)	6.32 (0.54)
5	3.17 (0.65)	2.98 (0.06)	5.82 (0.46)	5.97 (0.31)
all	3.20 (2.72)	2.94 (0.75)	6.47 (1.47)	6.14 (0.29)
<i>Periods 1-10</i>				
1	3.00 (0.00)	2.70 (0.65)	6.09 (2.13)	6.28 (0.51)
2	5.83 (5.97)	-	4.79 (2.27)	10.00 (0.00)
3	3.86 (1.00)	3.23 (0.52)	5.08 (1.83)	4.58 (2.00)
4	2.26 (2.28)	3.25 (1.10)	6.59 (1.38)	6.73 (1.10)
5	3.29 (0.76)	3.00 (0.00)	5.67 (0.58)	5.75 (0.46)
all	3.65 (2.00)	3.04 (0.57)	5.64 (1.64)	6.67 (0.81)
<i>Periods 17-26</i>				
1	3.30 (1.28)	2.88 (0.04)	8.79 (7.27)	6.22 (0.04)
2	2.95 (0.07)	2.94 (0.05)	6.16 (0.07)	6.49 (0.05)
3	2.90 (0.00)	2.90 (0.00)	6.07 (0.27)	5.70 (0.29)
4	2.90 (0.00)	2.83 (0.07)	8.94 (6.18)	6.32 (0.09)
5	2.90 (0.17)	2.96 (0.09)	6.10 (0.00)	5.97 (0.00)
all	2.99 (0.30)	2.90 (0.05)	7.21 (2.76)	6.13 (0.09)

Table 6: Average R&D contract proposals and standard deviations

the whole, the beginning or the end of the experiment. Further, it is unlikely that contract proposals were used as a cooperative signal to mislead the competitor, because once a proposal was done by a subject in a duopoly, the counterpart could always accept the contract such that the proposer was committed to it.

Another explanation could be that the contract proposals contained R&D decisions which were different from the cooperative level and thus not interesting for subjects to commit to. In table 6 the averages and standard deviations of proposed R&D decisions divided according to whether the contract was accepted or not, are presented for all duopolies. Note that averages of *individual* proposed R&D levels are taken and should thus be compared with the cooperative R&D level of one firm in duopoly. For both spillover levels we observe that proposed R&D decisions that are accepted in a contract are closer to the cooperative R&D level (i.e. 2.9 for $\beta = 0$ and 6.2 for $\beta = 1$) than proposed R&D decisions that are not accepted when considering all periods in the experiment. Also, standard deviations of R&D proposals that were not accepted are larger than standard deviations of accepted R&D

proposals. Thus, the fact that in some periods proposed R&D was too different from the cooperative R&D level, could have been a reason for subjects not to commit to a contract. In the last ten periods, for most duopolies the difference between average accepted and not accepted R&D proposals vanishes. For the first ten periods, we observe that proposed R&D levels that are either accepted or not, are in general not that close to the cooperative R&D level compared to the general averages¹⁵. Based on these observations, I would conclude that in general subjects learn to propose the cooperative R&D level in a contract, and learn at the same time to commit to it. In the beginning subjects make more mistakes when proposing and choosing ‘good’ R&D decisions.

Finally, remark that even contract proposals that contain the cooperative R&D level, are sometimes not accepted, especially in the last periods of the experiment. Probably, subjects occasionally try to deviate from the cooperative R&D level contracted in previous periods in the expectation that their counterparts keep choosing the cooperative R&D level, even when no contract is made. But if strategies of all subjects are more or less similar, it is eventually the Nash R&D level that arises in periods where no contracts are made.

To summarize, contracts do not arise in all periods for all duopolies and hypothesis 2 can thus be partly rejected. First, contract proposals do not always contain an R&D level that is close enough to the cooperative level, which is probably the reason why mainly at the beginning of the experiment less contracts are made than at the end of the experiment. In the beginning, subjects make more mistakes when proposing and choosing ‘good’ R&D decisions. Learning to do ‘good’ R&D proposals goes together with learning to commit to a contract. Secondly, even when contract proposals are ‘good’, in the sense that they are close to the cooperative R&D level, they are not always committed to. In those cases, subjects deviate in a sense from an R&D level on which they agreed, i.e. the R&D level in contracts of previous periods, and as such play a noncooperative strategy. The outcome for these cases is the competitive R&D level.

¹⁵These observations are confirmed in two-tailed Wilcoxon signed ranks tests. The null hypothesis is that no difference exists in the absolute value of the deviation of R&D decisions from the cooperative level, between periods without and with accepted contract proposals. When taking all periods in account, the p-value is 0.002, for averages of the first ten and last ten periods, the p-values are respectively 0.695 and 0.125.

5 Conclusion and remarks

In the paper I investigated in an experiment whether firms in duopoly compete or cooperate in R&D for two levels of technological spillovers, assuming Cournot competition in the output market. The experiment included a treatment without contract possibilities and a treatment with binding contract possibilities for each of the spillover levels (0 and 1). Three main findings on R&D behavior in the lab are reported. First, no significant differences in R&D behavior between the scenario without technological spillovers and the scenario with full spillovers are found. In this sense, behavior in the lab coincides with the theoretical predictions.

Secondly, I find that in the baseline treatments without contract possibilities, R&D decisions that maximized individual profit generally prevailed. Thus, the (subgame perfect) Nash equilibrium concept that is used in the noncooperative model of AJ described R&D behavior in the finitely repeated noncooperative game well.

The third finding is that in the contract treatments, observed R&D levels were close to the cooperative R&D level, only if contracts were actually committed to. Contracts were not always committed to, though. Especially in the beginning of the experiment less contracts were made, probably because contract proposals contained R&D levels that deviated from the cooperative level. This can partly be explained by the inexperience of the subjects in the first periods of the experiment. But also in the last periods, contracts were not always committed to, although proposals were close to the cooperative R&D level. Noncooperative Nash equilibrium play prevailed in those cases.

Policy conclusions that can be drawn from the findings in the experiment are to a certain extent similar to the policy conclusions that are based on the theoretical literature on cooperative and noncooperative R&D. Through allowing cooperation in the R&D stage in industries with large technological spillovers, higher levels of welfare can be reached. Allowing firms to commit to a binding R&D agreement does not always guarantee that firms actually commit to a contract, though, but it certainly helps to induce cooperative R&D levels. On the other hand, it is also important for government to be able to identify whether technological spillovers in industries are low or high, since also in industries characterized by low spillovers, R&D contracts are mostly committed to, if possible. It is clear that these policy conclusions hinge among others on the assumption that firms compete in the output stage, irrespective of whether the firms are engaged in an R&D cooperation project with other firms or not. Whether the formation of research joint ventures affects firms' decisions in the output stage, is left for further research.

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