Voluntary R&D cooperation in experimental duopoly markets

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Abstract

In the paper I examine in an experiment whether for two different levels of technological spillovers, cooperative R&D behavior voluntarily arises when firms have communication possibilities. It is assumed that in the output market, firms compete à la Cournot. Experimental results indicate that when technological spillovers are complete and subjects communicate, R&D decisions converge to the cooperative level, while in other cases R&D decisions converge towards the Nash equilibrium.

JEL codes: C90, L13, O31
Keywords: R&D, duopoly, experiment

1 Introduction

In recent years research joint ventures have become a widespread accepted form of cooperation between firms. US and European antitrust legislation prohibits firms to make agreements on selling price and quantity but provides an exception for agreements that are limited to the pre-competitive R&D stage. Moreover, R&D cooperation projects are actively supported and subsidized by many governments in their technology policies. Also in the

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theoretical industrial organization literature cooperative and non-cooperative R&D models have received much attention. Examples are d'Aspremont and Jacquemin (1988); Kamien et al. (1992); Poyago-Theotoky (1995); Leahy and Neary (1997); Petit and Tolwinski (1999); Hinloopen (2000). In this strand of literature, the degree of technological spillovers between firms determines whether it is welfare-improving that firms either compete or cooperate in R&D, given that they compete in the output stage. If spillovers are above a certain threshold, R&D investment and welfare are higher under R&D cooperation, while for spillovers below the threshold, R&D competition yields higher R&D and welfare. This is often viewed as a rationale for government stimulation of R&D cooperation in industries characterized by large technological spillovers.

In the above theoretical models, the emergence of R&D cooperation is only examined in a fully cooperative context, meaning that the implicit assumption is made that firms can credibly commit, e.g. in a binding agreement, to the cooperative R&D level. But can R&D cooperation in some circumstances also be sustainable in a non-cooperative context, as e.g. tacit price or quantity collusion is under some conditions in oligopoly markets? In Holt (1995) some examples are given of experiments on oligopoly games in which non-binding communication tends to increase cooperation. Examples of other oligopoly pricing games with non-binding communication are Holt and Davis (1990), Cason (1995) and Harstad et al. (1998). Harstad et al. (1998) find that the announcement of prices leads to higher prices than the Nash equilibrium, though not as high as the joint profit maximization level. In Holt and Davis (1990) evidence is found that initially prices increase after price announcements but that in the end prices return to their initial lower levels. Cason (1995) comes to a similar conclusion but distinguishes effects of discrete and continuous signaling. Continuous signaling, where it is optional to send a signal, stimulates cooperation more, which implies that the simple sending of a signal indicates a willingness to cooperate. Thus, with an appropriate form of non-binding communication, cooperation in prices or quantities is higher than without communication.

In this paper an experiment is set up to investigate whether in a non-cooperative R&D game, assuming Cournot competition in the output stage, R&D cooperation naturally arises under some conditions. As non-binding communication has already showed to be effective in raising cooperation in other oligopoly experiments, I allow for it in part of the treatments. In the other treatments, subjects do not have any communication possibilities. Given the importance of the technological spillovers in the theoretical literature, I ran both treatments for a scenario without spillovers and a scenario with complete spillovers. Results indicate that communication yields R&D

levels that are close to the cooperative outcome when technological spillovers are large, while without spillovers the possibility of communication does not make a difference. In the latter case R&D levels converge to the Nash prediction. In the baseline treatments, Nash predictions perform well.

Earlier experiments on R&D behavior contained e.g. patent races (Hey and Reynolds, 1991; Sbriglia and Hey, 1994) or 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 (Isaac and Reynolds, 1986, 1988, 1992). In the latter series of experiments, 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 as firms also compete in a product market. Main conclusions are that risk-neutral non-cooperative Nash equilibrium predictors perform relatively well and that a reduction in appropriability for the innovator leads to reduced R&D spending by all participants. The experimental results further 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. Another paper that addresses the issue of technological spillovers in an R&D experiment is Jullien and Ruffieux (2001). In their experiments firms could either adopt an existing technology or develop a new technology with uncertainty over the outcome and also competed in a product market. 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. No influence of spillovers on R&D incentives has been found. Finally, in Suetens (2003) R&D behavior of firms that compete in quantities and that have binding contract possibilities is examined. Conclusions are that, irrespective of the level of technological spillovers, committing to an R&D contract guarantees that R&D decisions are at the cooperative level, and that in other cases non-cooperative Nash predictions perform well.

The link between spillovers and voluntary incentives to choose cooperative R&D levels, either with or without non-binding communication has not been addressed in previous experiments. The paper is organized as follows. In section 2, the model on which the experiment is based, is resumed. Section 3 contains the experimental design and analyses of the experimental results are presented in section 4. In section 5, I elaborate on what has been communicated and section 6 concludes.

2 Theoretical benchmarks

The model on which the theoretical predictions and benchmarks are based, is in d'Aspremont and Jacquemin (1988). For our purposes, it is assumed 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. An industry with two 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 form $P(Q) = a - bQ$, with $a, b > 0, Q = Q_1 + Q_2$ and Q_i is production quantity of firm i. The linear 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 β 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. Unit cost of firm i assumed to be linearly decreasing in its amount of effective R&D and thus is $c_i(X_i) = \alpha - \gamma X_i$ with $\gamma > 0, \alpha < a$. Further, R&D investments are assumed to have decreasing returns, which is implemented in the model in the form of a quadratic R&D cost function[1] $f_i(x_i) = \delta \frac{x_i^2}{2}$ with $\delta > 0$.

The two-stage game is solved by backward induction. 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 in terms of the first-stage decision variables:

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

In the first stage firms maximize their profit with respect to R&D which yields the following (symmetric) equilibrium R&D level[2]:

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

The subgame perfect Nash prediction of the one-shot and the finitely repeated static R&D game, assuming Cournot competition in the output market, is

[1] In 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.

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

x^*. For the most widely separated levels of technological spillovers, i.e. $\beta = 0$ and $\beta = 1$[3], and parameter values $a = 250$, $b = 5$, $\alpha = 100$, $\gamma = 2$ and $\delta = 5$[4] Nash predictions are the following

$$x^* = \begin{cases} 5.74 & : \quad \beta = 0 \\ 2.87 & : \quad \beta = 1 \end{cases}$$

Another theoretical benchmark arises when firms coordinate their R&D activities as to maximize the sum of their profits[5]. In this case, the symmetric maximization problem $\max_{x_i} \sum_{i=1}^{2} \pi_i^{\mathrm{e}}$ with $x_i > 0$, should be solved for $i = 1, 2$, which results in the following unique outcome for R&D[6]:

$$x^{**} = \frac{2\gamma(a-\alpha)(1+\beta)}{9b\delta - 2\gamma^2(1+\beta)^2} \qquad \forall i = 1, 2. \tag{3}$$

For the above parameter values the cooperative outcomes are

$$x^{**} = \begin{cases} 2.76 & : \quad \beta = 0 \\ 6.22 & : \quad \beta = 1. \end{cases}$$

3 Experimental procedure

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 experiment consisted of three computerized experimental sessions with a total of 46 participants, recruited from undergraduate economics courses and divided into fixed groups of two (duopolies). 20 students participated in the treatments without technological spillovers and 26 in the treatments with spillovers. The students were not informed about the identity of their competitor. Each of the sessions took less than 80 minutes. In

[3] In the experiment cases without and with full spillovers are used to sharpen possible contrasts in the results (Friedman and Sunder, 1994).

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

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

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

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 $[0, 25]$[7] 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 in all except the first periods, 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).

For both spillover levels I allowed for the possibility of 'cheap talk' communication in part of the duopolies (in 5 for $\beta = 0$ and in 8 for $\beta = 1$). In these duopolies, subjects were asked to send messages each period to their competitors with an indication of the interval — which could be a number or the maximum interval of $[0, 25]$ — in which their decision would be situated in the considered period. Communicating the interval $[0, 25]$ should be interpreted as an unwillingness to communicate, so in our experiment subjects always have an option not to communicate. This resembles the continuous signaling treatment in Cason (1995). Since the communication is not binding, the theoretical prediction is the Nash R&D level.

As such, four treatments were run. That is 'no chat' and 'chat' for technological spillovers of 0 and 1. Sixteen subjects were appointed to the treatment with spillovers and communication possibilities and ten subjects to each of the other treatments.

[7]This interval was necessary to obtain positive values for unit production cost.

4 Experimental results

In the experiment, observations within the duopolies are not independent, since duopolists are or could be influenced by their competitor's behavior in making their R&D decisions. Using the sum of R&D decisions by duopoly in all analyses, circumvents this problem and creates independent observations per duopoly. The sum of R&D decisions by duopoly is called X. Period 0 is ignored such that for each subject, the time series amounts to 26 periods. As the theoretical outcomes (the Nash and cooperative R&D level) are symmetric, the theoretical duopoly outcomes are twice the individual outcomes. Table 1 represents the duopoly Nash (*) and cooperative (**) R&D levels.

	$\beta = 0$	$\beta = 1$
X^*	11.48	5.74
X^{**}	5.53	12.44

Table 1: Theoretical duopoly R&D benchmarks

In figure 1 a box plot of averages of the R&D decisions of each duopoly over all 26 periods is presented. Data of each of the 4 treatments are grouped. The box in the plot represents the inter quartile range of the data and the whiskers represent the highest and lowest values excluding outliers and extreme values. The dotted line is the median. Extreme values are defined as observations that are more than 3 box lengths from the upper or lower edge of the box. One duopoly in the treatment with $\beta = 0$ and without chat or contract possibilities is identified as an extreme value (marked with a star).

It is observed that in the no-spillover treatments, either with or without communication possibilities, the medians of the average duopoly R&D decisions are quite close to the Nash equilibrium prediction. In the complete spillover treatments the medians of R&D decisions in both treatments are not that similar. Without communication, they are close to the Nash equilibrium, while with communication they are closer to the cooperative level. With communication and spillovers a high variance in R&D decisions is observed though. Summarizing, at first sight the non-cooperative communication possibilities seem not to make a difference in R&D behavior when no technological spillovers exist and Nash equilibrium predictions perform quite well. With spillovers, R&D levels are closer to the cooperative level when cheap talk is allowed compared to when it is not allowed.

I further compared average R&D decisions of the duopolies in the last ten periods in the chat and contract treatments with the decisions in the

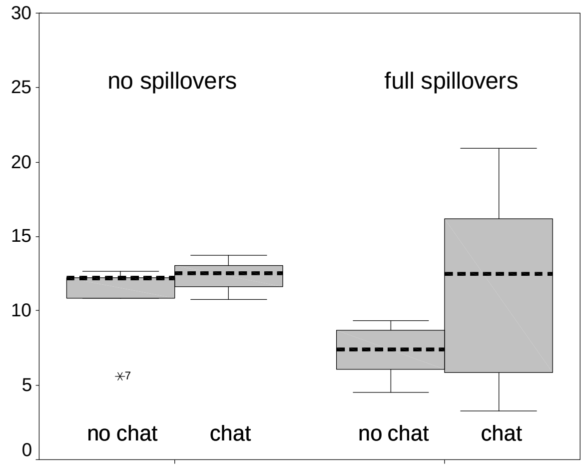

Figure 1: Boxplot

	Between		Within	
	$\beta = 0$	$\beta = 1$	$\beta = 0$	$\beta = 1$
z	-0.104	-1.464	-1.604	-1.753
exact sig. (2-tailed)	1.000	0.171	0.250	0.126
exact sig. (1-tailed)	0.500	0.086	0.125	0.063

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

treatments without any contract or communication possibilities, using Mann-Whitney tests. Results of these tests are in table 2, in the part under the header ‘Between’. The null hypothesis is that R&D decisions without communication possibilities do not differ from R&D decisions with communication possibilities. For the treatments without technological spillovers, no statistically significant difference is found between ‘chat’ and ‘no chat’. In the case of complete spillovers some evidence for a difference between ‘chat’ and ‘no chat’ is found, when relying on one-tailed test results and using a 10% significance level. In this case the alternative hypothesis would be that R&D levels with chat are higher than those without chat if it is expected that communication possibilities would stimulate R&D cooperation. But statistical evidence is not that overwhelming to make clear-cut conclusions regarding the effect of communication at this stage.

In the Mann-Whitney tests it is not taken into account whether subjects have actually used the communication possibilities. In another series of tests, reported in the same table under the header 'Within', I have corrected for this. The results are those of Wilcoxon signed ranks tests of differences between average R&D levels within the communication treatments when communication possibilities have actually been used by both subjects in a duopoly and R&D levels averaged over periods in which these possibilities have not been used. Again, only observations in the last ten periods were used to compute averages. Note that the number of sent messages in duopolies with technological spillovers does not significantly differ from the scenario without spillovers. 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 communicate intervals in which the R&D decision will be (with 10% significance). With respect to the no-spillover treatment, it is found that no differences in R&D decisions arise between R&D decisions in periods with and without communication. On the basis of non-parametric tests it is possible to compare observations between and within treatments. In what follows an econometric analysis is performed to compare the experimental R&D decisions with the Nash and cooperative outcomes.

The data are structured in a way, in which non-parametric tests 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, ignoring period 0. That is why in what follows I use econometric techniques to further analyze the data. 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 I estimate the following equation[8]

$$X_{k,l,t} = \lambda_{k0} + \lambda_{k1} X_{k,l,t-1} + \lambda_{k2} X_{k,l,t-2} + \epsilon_{k,l,t}, \tag{4}$$

with $\epsilon_{k,l,t}$ following a white noise process. An estimate for the long-term equilibrium θ_k is computed as follows: $\theta_k = \lambda_{k0}/(1 - \lambda_{k1} - \lambda_{k2})$. The series is stationary and thus converges if $|\lambda_{k1}| < 1$, $|\lambda_{k2}| < 1$, $\lambda_{k1} + \lambda_{k2} < 1$ and $\lambda_{k2} - \lambda_{k1} < 1$ (Greene, 2000).

For each of the treatments I have estimated a model as in (4). The choice of 2 lags in the autoregressive process is rather arbitrary, although with

[8]As in Mason and Phillips (1997) it is assumed that the R&D decision of each 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 (θ_k), and a subject- and time-specific random or residual fluctuation ($u_{k,l,t}$). I.e., $X_{k,l,t} = \theta_k + u_{k,l,t}$, where k represents the treatment, l the duopoly and t the period. This assumption combined with the assumption that a pair's R&D decisions are correlated with R&D decisions in previous periods, i.e. that the residuals follow an AR(2) process ($u_{k,l,t} = \lambda_{k1} u_{k,l,t-1} + \lambda_{k2} u_{k,l,t-2} + \epsilon_{k,l,t}$), yields the above econometric equation.

	no chat					chat			
	$\beta = 0$		$\beta = 1$			$\beta = 0$		$\beta = 1$	
$\hat{\lambda}_{k0}$	3.64	[.000]	1.77	[.000]	$\hat{\lambda}^0_{k0}$	9.83	[.000]	0.18	[.658]
$\hat{\lambda}_{k1}$	0.35	[.000]	0.47	[.000]	$\hat{\lambda}^0_{k1}$	0.25	[.009]	0.68	[.000]
$\hat{\lambda}_{k2}$	0.28	[.000]	0.20	[.000]	$\hat{\lambda}^0_{k2}$	0.02	[.843]	0.20	[.000]
					$\hat{\lambda}^1_{k0}$	-1.64	[.022]	1.54	[.002]
					$\hat{\lambda}^1_{k1}$	-0.09	[.144]	0.01	[.858]
					$\hat{\lambda}^1_{k2}$	0.10	[.057]	-0.03	[.281]
$\hat{\theta}_k$	9.86	(0.39)	5.36	(0.40)	$\hat{\theta}^0_k$	13.47	(1.07)	1.51	(3.05)
					$\hat{\theta}^1_k$	11.40	(0.30)	12.32	(1.12)
$GOF^{(a)}$	0.16		0.85		$GOF^{(a)}$	0.24		0.47	
Durbin-h$^{(b)}$	1		2		Durbin-h$^{(b)}$	0		1	
N*T	5*24		5*24		N*T	5*24		8*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

2 lags one should in general be able to correct for possible autocorrelation problems without losing too many degrees of freedom. As statistical evidence has been found for differences within the communication treatments in the sense that it mattered whether communication possibilities have actually been used by the subjects, a dummy is included in the econometric equations. This dummy is equal to one if an interval has been sent in that period by both subjects in the duopoly and equal to zero otherwise. As to allow for different slopes, 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 usual parameter estimates and the estimates taking into account the dummy, respectively. The sums of $\hat{\lambda}^0_{ki}$ and $\hat{\lambda}^1_{ki}$ for $i = 0, 1, 2$ are used to compute respectively the constant term and the slopes when communication possibilities are used, while when no communication possibilities are used, the constant term and the slopes are respectively $\hat{\lambda}^0_{ki}$ for $i = 0, 1, 2$. As tests indicated possible within-heteroskedasticity for some equations, standard errors were estimated heteroskedastic-consistently. The standard errors of the static long-run equilibria have been calculated according to corollary 4.2.2. 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. Removing the outlier in treatments 'no spillover, no chat' yielded estimates that are closer to Nash predictions. 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 in most cases, which indicates that differences exist within the communication treatments between R&D levels of subjects that have used the communication possibilities and those that have not used them.

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 dummies.

	spillover = 0		spillover = 1	
	no chat	chat	no chat	chat
H_0: $\theta^0_k = X^*$	-4.16^{++}	1.92	-0.96	-1.39
H_0: $\theta^0_k = X^{**}$	11.03^{++}	7.66^{++}	-17.66^{++}	-3.59^{++}
H_0: $\theta^1_k = X^*$	-	-0.26	-	5.90^{++}
H_0: $\theta^1_k = X^{**}$	-	19.86^{++}	-	-0.11

Without the outlier, the t-values are respectively 1.87 and 26.10. instead of -4.16 and 11.03.
$^{++}H_0$ is rejected with $\alpha = 0.05$ (critical t value is 1.98).

Table 4: Results of t-tests

From the t-tests it can be concluded that R&D behavior of subjects with complete spillovers and no communication 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. With communication possibilities, R&D behavior does neither significantly differ from competitive Nash behavior without spillovers, irrespective of whether intervals are actually sent. With spillovers, it does matter whether communication possibilities have actually been used by subjects. Indeed, only for those cases in which messages have been sent, no statistically significant difference is found between R&D levels in the experiment and cooperative R&D levels. The R&D level that corresponds to behavior of non-communicating subjects does not significantly differ from the Nash prediction, mainly because of it's high variance (see table 3). Thus, the subgame perfect Nash equilibrium predicts R&D behavior well for treatments without technological spillovers, either with or without communication. R&D behavior in periods in which intervals were communicated in the treatment with technological spillovers, is cooperative.

To summarize, when no technological spillovers are present, subjects need more 'bindingness' than simple sharing intentions about R&D decisions as to deviate from the Nash R&D level and to converge to the cooperative level (cfr. Suetens, 2003). When R&D investment is characterized by complete technological spillovers, the sending of messages containing intended R&D investment suffices for R&D behavior to be cooperative.

A first plausible explanation for the difference between R&D behavior without and with spillovers in the non-cooperative communication treatment can be looked for in non-cooperative theory of infinitely repeated games (Friedman, 1971; Martin, 1993). If strategies were followed as if the game was an infinitely repeated game[9], it matters whether a large difference exist between the maximum profit that would be gained when defecting compared to the profit that would be gained when cooperating for several periods. If the discount factor that subjects use to calculate the present value of their expected future profits is below a certain threshold, which is a function of the difference between maximum profit when defecting and cooperative profit, such a strategy is a non-cooperative equilibrium. This threshold is equal to $(\pi^{**} - \pi^{*})/(\hat{\pi} - \pi^{**})$ where $\hat{\pi}$ is the profit that is gained when a firm maximizes own profit, assuming that the other chooses the joint profit maximizing level. If the threshold is higher under complete spillovers than without spillovers, subjects in the former treatments will cooperate easier than subjects in the latter. In the parameter settings of the experiment the threshold for both treatments is 0.96 which implies that incentives of firms to cooperate are expected to be the same for both spillover levels. Thus, if the game is viewed as an infinitely repeated game, cooperation is as likely to be a viable strategy for complete spillovers as it is for the model without spillovers.

[9] An example is a trigger strategy, where a firm in duopoly chooses to cooperate until the end of the game, if the other also chooses to cooperate. If one firm defects, the other will also choose to compete.

Thus, an explanation for the difference in behavior in both treatments should be sought elsewhere.

Secondly, compare the R&D game to a public goods/bads game. Public goods games and R&D games with high spillovers are characterized by positive externalities, since an action of one subject increases profit of other subjects. In public bad games and R&D games with low spillovers the opposite is valid as an action of one subject leads to a decline in profit of the other subjects such that negative externalities appear. Experiments on public goods typically yield higher levels of cooperation than their public bad equivalents (Andreoni, 1995; Offerman, 1996; Willinger and Ziegelmeyer, 1999; Cookson, 2000; Park, 2000), which in this context is often referred to as a framing effect. My findings coincide to some extent with these results, at least when subjects communicate. I would not call the effect a framing effect, though, since the no-spillovers and the full-spillovers game are not symmetric in the sense that they have differently sloping reaction curves. Public goods and bads games are both characterized by a horizontal reaction curve.

A third explanation is a rather intuitive one and related to this. Reaction curves have a negative slope when $\beta = 0$ and a positive slope when $\beta = 1$, since R&D decisions are strategic substitutes when $\beta < 0.5$ and strategic complements when $\beta > 0.5$ (Kamien et al., 1992; Hinloopen, 2000). Thus, without spillovers, the best response of a firm to an increase in R&D of the competitor, is to decrease it's own R&D. This could hamper the formation of cooperative agreements[10]. With high spillovers, the opposite effect plays. A theoretical paper on the relation between strategic complementarity/substitutability, externalities and ambiguity is Eichberger and Kelsey (2002). Ambiguity, referring to "situations in which individuals have to make decisions when the relevant probabilities are unknown", would decrease efforts or actions. Since in non-cooperative games with strategic substitutes (complements) and negative (positive) externalities, Nash equilibrium predictions are higher (lower) than Pareto superior cooperative outcomes, this would imply that if ambiguity were present, in no-spillover (complete spillover) games, R&D decisions would be biased towards cooperative (competitive) levels. Since I found evidence for competitive R&D behavior in the no-spillover treatments, the presence of ambiguity is quite unlikely. With spillover levels of one, ambiguity neither is likely in the presence of communication. Without communication, behavior in the experiments is competitive, which theoretically provides an argument for the existence of ambiguity. But since the set-up in this treatment is the same as in the other treatments, it can be assumed that ambiguity neither is present. In any case, possi-

[10] I thank Jan Potters for suggesting this.

ble differences in behavior when actions are strategic substitutes or strategic complements is a topic that requires some further (experimental) research.

5 Communication

As to further investigate why chatting was successful in achieving cooperative R&D levels with full spillovers and why it was not without spillovers, in this section I take a closer look at what exactly has been communicated by the subjects. In table 5 data are given on the communicated intervals and their contents. The data refer to numbers of observed intervals and are aggregated in time and across duopolies. Remark that for small intervals it is less likely that they contain either the Nash or the cooperative R&D level, while one of the two bounds can still be very close to either of the R&D levels. If ignoring these communicative messages, the communicative extent of the messages would be underestimated. To correct for this, the smaller intervals were enlarged. Moreover, for the intervals of which the difference between the upper bound and the lower bound was strictly smaller than 2, lower (upper) bounds were recalculated by subtracting (adding) 0.5[11]. If it is assumed that communication of the interval $[0, 25]$ represents an unwillingness to communicate, only intervals not equal to $[0, 25]$ should be considered when investigating the communicative contents of the chats. In the first part of the table the data are divided into intervals equal and not equal to $[0, 25]$. Slightly more (though not statistically significant) unwillingness to communicate is observed in the no-spillovers treatment than in the full-spillovers treatment. Furthermore, the by far largest part of the communicated intervals $[0, 25]$ (about 85 out of 108) for $\beta = 1$ comes from two out of eight duopolies. The intervals $[0, 25]$ in the no-spillovers treatment come almost exclusively from three out of five duopolies.

In the second part of the table, the communicated intervals are further subdivided into four groups, i.e. whether they do not contain the theoretical Nash nor the cooperative R&D decision, whether they contain both, whether they only contain the Nash R&D equilibrium and whether they only contain the cooperative R&D equilibrium. For both spillover levels, the share of intervals not containing any equilibrium is quite high, which could be an indication that communication occasionally is simple 'babbling'. For both spillover treatments, the majority of these messages differ a lot from the co-

[11] A total of 213 intervals out of 676 were re-scaled. Note that the original size (upper minus lower bound) of only 2 out of these 213 intervals was between 1 and 2. This implies that only those two were re-scaled to a size slightly larger than 2. As such, the 'new' size of most intervals, i.e. 211, was still smaller than or equal to 1.

	spillover = 0		spillover = 1	
interval= $[0, 25]$	84	32%	108	26%
concentration	$41^{(a)}$	16%	$85^{(b)}$	20%
	$82^{(c)}$	32%		
interval$\neq [0, 25]$	176	68%	308	74%
total	260	100%	416	100%
$x^*, x^{**} \notin$ interval	73	41%	150	49%
$x^*, x^{**} \in$ interval	2	1%	16	5%
only $x^* \in$ interval	79	45%	19	6%
only $x^{**} \in$ interval	22	12%	123	40%
total	176	100%	308	100%

(a) 1 out of 5 duopolies.
(b) 2 out of 8 duopolies.
(c) 3 out of 5 duopolies.

Table 5: Descriptives on communicated intervals

operative R&D level. For $\beta = 1$ they are usually higher than the equilibrium cooperative R&D level. The percentage of intervals containing both, Nash and cooperative R&D levels, is very low for both spillover levels.

Concentrating on intervals that are informative, in the treatment without spillovers 45% of the intervals only contains the Nash R&D prediction, while 12% only contains the optimal cooperative R&D level. In the treatment with spillovers the opposite is observed, i.e. 40% only contains the cooperative equilibrium and 6% the Nash. This would suggest that either the ability to find the cooperative R&D level or the willingness to cooperate is higher with spillovers compared to without spillovers, which coincides with the results in the previous section. Whether the difference in communicating competitive and cooperative intervals between both spillover treatments is statistically significant, has been tested by Mann-Whitney tests. The null hypothesis that the number of times an interval contains the competitive R&D level is equal for $\beta = 0$ and $\beta = 1$ is rejected against the alternative hypothesis that it is higher for $\beta = 0$ than for $\beta = 1$ with a significance level of 1% (p-value is 0.003). Further, the null hypothesis that the number of times an interval contains the cooperative R&D level is equal for $\beta = 1$ and $\beta = 0$ is only rejected with a significance level of 10% (p-value is 0.088) against the alternative hypothesis that it is higher for $\beta = 1$ than for $\beta = 0$.

To summarize, if intervals were communicated, they often contained relevant information about intended R&D behavior. With spillovers, intended R&D levels were generally closer to the cooperative level, while without spillovers to the Nash level. This could indicate that the observed cooperative R&D behavior in the non-cooperative treatment with communication is a result of having communicated 'cooperative intervals'.

6 Conclusion and remarks

In the paper I investigated in an experiment whether firms in duopoly compete or cooperate in R&D under two modes of agreement possibilities and for two levels of technological spillovers, assuming Cournot competition in the output market. The experiment included a treatment without any communication or contract possibilities, a treatment with non-binding communication possibilities and a treatment with binding contract possibilities for each of the spillover levels (0 and 1).

Competing in R&D is the game theoretical prediction of behavior in the finitely repeated game with or without non-binding communication possibilities. In the treatments without communication possibilities, Nash R&D behavior prevailed for the scenarios with and without technological spillovers. In the case of complete spillovers, behavior in periods in which messages have actually been sent, converged to R&D cooperation. Without spillovers, Nash behavior prevailed also in the communication treatment. Thus, results support to some extent that when spillovers are high enough, firms have more incentives to choose cooperative R&D levels compared to when spillovers are low in a non-cooperative environment. If no technological spillovers are present, subjects need more 'bindingness' than simple sharing intentions about R&D decisions as to deviate from the Nash R&D level and to converge to the cooperative level (cfr. Suetens, 2003). For R&D investment subject to high technological spillovers, the sending of messages containing intended R&D investment suffices for R&D behavior to be cooperative. An interpretation of these results could be that in industries characterized by high technological spillovers, government stimulation of R&D cooperation through contracts is not necessary when firms' representatives or R&D managers communicate or meet, as cooperation in R&D then arise in a natural way.

Our results also coincide to some extent with earlier found evidence in public goods experiments that with positive (negative) externalities, which imply that actions increase (decrease) profits of all parties, subjects contribute more (less) to the public good and thus cooperate more (less). Related to this is the issue of strategic properties of actions. It is left for further research whether differences in cooperation levels are dependent of actions being strategic substitutes or complements.

References

R. Amir. Modelling imperfectly appropriable R&D via spillovers. *Journal of Industrial Organization*, 18:1013–32, 2000.

J. Andreoni. Warm-glow versus cold-prickle: the effects of positive and negative framing on cooperation in experiments. *Quarterly Journal of Economics*, 60:1–14, 1995.

T.N. Cason. Cheap talk price signaling in laboratory markets. *Information Economics and Policy*, 7:183–204, 1995.

R. Cookson. Framing effects in public goods experiments. *Experimental Economics*, 3:55–79, 2000.

C. d'Aspremont and A. Jacquemin. Cooperative and noncooperative R&D in duopoly with spillovers. *American Economic Review*, 78(5):1133–7, 1988.

J. Eichberger and D. Kelsey. Strategic complements, substitutes and ambiguity: the implications for public goods. *Journal of Economic Theory*, 106 (2):436–66, 2002.

T.B. Fomby, R.C. Hill, and S.R. Johnson. *Advanced econometric methods*. Springer-Verlag, New York, 1984.

D. Friedman and S. Sunder. *Experimental methods - A primer for economists*. Cambridge University press, Cambridge, 1994.

J.W. Friedman. A non-cooperative equilibrium for supergames. *Review of Economic Studies*, .38(1):1–12, 1971.

W. H. Greene. *Econometric analysis*. Prentice-Hall, New Jersey, 2000.

R. Harstad, S. Martin, and H. Normann. Experimental tests of consciously parallel behaviour in oligopoly. In L. Phlips, editor, *Applied Industrial Organization*. Cambridge University Press, Cambridge, 1998.

I. Henriques. Cooperative and noncooperative R&D in duopoly with spillovers: comment. *American Economic Review*, 80:638–40, 1990.

J.D. Hey and M.L. Reynolds. Experiments, games and economics. In S. Moss and J. Rae, editors, *Artificial intelligence and economic analysis*, pages 81–115. Edwar Elgar, Aldershot, 1991.

J. Hinloopen. Strategic R&D cooperatives. *Research in Economics*, 54(2): 153–86, 2000.

C.A. Holt. Industrial organization: a survey of laboratory research. In J.H. Kagel and A.E. Roth, editors, *The handbook of experimental economics*, pages 349–444. Princeton University Press, New Jersey, 1995.

C.A. Holt and D. Davis. The effects of non-binding price announcements on posted-offer markets. *Economics Letters*, 34:307–10, 1990.

R.M. Isaac and S.S. Reynolds. Innovation and property rights in information: an experimental approach to testing hypotheses about private R&D behaviour. In G. Libecap, editor, *Advances in the study of entrepreneurship, innovation, and economic growth, volume 1*, pages 129–56. Jai Press, Greenwich, 1986.

R.M. Isaac and S.S. Reynolds. Appropriability and market structure in a stochastic invention model. *Quarterly Journal of Economics*, 103:647–71, 1988.

R.M. Isaac and S.S. Reynolds. Schumpeterian competition in experimental markets. *Journal of Economic Behaviour and Organization*, 17:59–100, 1992.

C. Jullien and B. Ruffieux. Innovation, avantages concurrentiels et concurrence. *Revue d'Economie Politique*, 111(1):121–50, 2001.

M.I. Kamien, E. Muller, and I. Zang. Research joint ventures and R&D cartels. *American Economic Review*, 82(5):1293–306, 1992.

M. Königstein. Measuring treatment- effects in experimental cross-sectional time series. In M. Königstein, editor, *Equity, efficiency and evolutionary stability in bargaining games with joint production*. Springer, Berlin, 2000.

D. Leahy and J.P. Neary. Public policy towards R&D in oligopolistic industries. *American Economic Review*, 87(4):642–62, 1997.

S. Martin. *Advanced industrial economics*. Blackwell Publishers, Cambridge, 1993.

C. F. Mason and O. R. Phillips. Information and cost asymmetry in experimental duopoly markets. *Review of Economics and Statistics*, 79(2):290–9, 1997.

T. Offerman. *Beliefs and decision rules in public good games: theory and experiments*. PhD thesis, Tinbergen Institute, University of Amsterdam, 1996.

E. Park. Warm-glow versus cold-prickle: a further experimental study of framing effects on free-riding. *Journal of Economic Behavior and Organization*, 43:405–21, 2000.

M.L. Petit and B. Tolwinski. R&D cooperation or competition? *European Economic Review*, 43(1):185–208, 1999.

J. Poyago-Theotoky. Equilibrium and optimal size of a research joint venture in an oligopoly with spillovers. *Journal of Industrial Economics*, 43(2): 209–26, 1995.

S.W. Salant and G. Shaffer. Optimal asymmetric strategies in research joint ventures. *International Journal of Industrial Organization*, 16:195–208, 1998.

P. Sbriglia and J.D. Hey. Experiments in multi-stage R&D competition. *Empirical Economics*, 19:291–316, 1994.

S. Suetens. A duopoly experiment on cooperative and noncooperative R&D, 2003. Mimeo.

M. Willinger and A. Ziegelmeyer. Framing and cooperation in public good games: an experiment with an interior solution. *Economics Letters*, 65: 323–28, 1999.