An Experimental Analysis of Dynamic Incentives to Share Knowledge

Cary Deck & Nisvan Erkal

August 2009

Research Paper Number 1083

An Experimental Analysis of
Dynamic Incentives to Share Knowledge[1]

Cary Deck[2] and Nisvan Erkal[3]

August 2009

[2]Department of Economics, University of Arkansas, Fayetteville, AR 72701, USA. cdeck@walton.uark.edu.

[3]Department of Economics, University of Melbourne, Victoria 3010, Australia. n.erkal@unimelb.edu.au.

Abstract

Knowledge sharing arrangements are an important part of the innovation process as they help firms acquire technological capabilities, shorten development time, and spread risk and cost. A question central to the study of knowledge sharing arrangements is the impact of competition on cooperation. While cooperation has the benefit of avoiding duplication, it may have an adverse effect on the competitive advantage of a leading firm. Hence, firms face a difficult challenge during the innovation process while deciding which components of it, if any, to carry out in collaboration with other firms. This paper reports the results of controlled laboratory experiments which identify how the decision to form research joint ventures changes with both relative progress during the R&D process and the intensity of product market competition. The design is based on a modified version of Erkal and Minehart (2008). The results indicate that if expected profits are such that the lagging firms always stay in the race, cooperation unravels as firms move forward in the discovery process and as monopoly profits become relatively more attractive. These results are generally consistent with the theoretical predictions.

1   Introduction

Development of new technologies plays an increasingly important role in firms' competitiveness. Research projects in many industries involve multiple steps and can take several years to complete. One way in which firms can attempt to acquire the incremental knowledge they need during the innovation process is by collaborating with their rivals. A question central to the study of such knowledge sharing arrangements is the impact of competition on cooperation. While cooperation helps firms acquire technological capabilities, shorten development time, and spread risk and cost, it may have an adverse effect on the competitive advantage of a leading firm. Hence, firms face a difficult challenge during the innovation process while deciding which components of it, if any, to carry out in collaboration with other firms.

The aim of this paper is to identify, by using controlled laboratory experiments, how the decision to form research joint ventures changes with both relative progress during the R&D process and the intensity of product market competition. The design is based on a modified version of Erkal and Minehart (2008), who develop a theoretical framework studying the dynamics of private sharing incentives during the innovation process. They analyze the impact of competition on the incentives to cooperate at different stages of the R&D process. Their results show that sharing dynamics depend on both how close the firms are to product market competition and how intense that competition is, as measured by the magnitude of duopoly profits relative to monopoly profits. If duopoly profits are relatively low, a lagging firm in the R&D race exits when it falls behind. In this case, the incentives to share intermediate research outcomes may be weakest early on. If duopoly profits are relatively high, a lagging firm pursues duopoly profits rather than exiting. In this case, the incentives to share intermediate research outcomes decrease monotonically with progress. That is, if firms do not find it optimal to cooperate at a particular step, they do not find it optimal to cooperate at a later step.

Understanding the predictive power of this theoretical framework and the dynamics of sharing more generally are important for effective policy making. The methodology

1

of experimental economics is an ideal tool for testing the implications of such a theoretical framework as it allows us to control the critical features of the model, including the dynamic process governing innovation and the product market payoffs. We test the implications of Erkal and Minehart (2008) by focusing on the region of the parameter space where a lagging firm never finds it optimal to exit the race. Our results are in general consistent with the theoretical predictions. We demonstrate that cooperation unravels as firms move forward in the discovery process and as monopoly profits become relatively more attractive. However, the observed behavior tends to be more cooperative than predicted, which is not uncommon in laboratory experiments.

There exists a large body of theoretical literature on cooperative R&D, primarily focusing on the incentives to cooperate in the presence of technological spillovers in a static set-up.[1] Erkal and Minehart (2008) differs from this literature by focusing on the dynamic aspects of sharing incentives. Although the link between spillovers and firms' incentives to cooperate have been studied in a number of empirical papers with mixed results,[2] there are no empirical studies addressing the dynamic aspects of sharing incentives. In the experimental literature, although a small group of papers have analyzed the incentives to invest in R&D (e.g., Isaac and Reynolds, 1988 and 1992; Hey and Reynolds, 1991; Sbriglia and Hey, 1994; and Zizzo, 2002), the incentives to cooperate have only been analyzed by Silipo (2005) and Suetens (2005). Suetens (2005) analyzes the incentives for cooperative R&D in a static environment with spillovers and finds that the experimental R&D decisions are close to the predicted level. Silipo (2005) analyzes the incentives to cooperate in a deterministic, winner-take-all, multi-step innovation process, where firms make cost-reducing investments, and finds that cooperation increases as the level of monopoly profits (i.e., the

---

[1]See, for example, d'Aspremont and Jacquemin (1988), Kamien et al. (1992), Suzumara (1992), Choi (1993), Vonortas (1994), Poyago-Theotoky (1995), Leahy and Neary (1997), Salant and Shaffer (1998), Martin (2002), Amir (2000), Amir and Wooders (2000), and Erkal and Piccinin (2008). See De Bondt (1997) for a survey.

[2]Cassiman and Veugelers (2002) find that the incentives to cooperate in R&D are lower when outgoing spillovers are high, but they are higher when incoming spillovers are high. Hernan et al. (2003) find a positive relationship between outgoing spillovers and incentives to cooperate. Kaiser (2002) finds that (horizontal) spillovers increase the probability to cooperate in R&D while Belderbos et al. (2004) find no significant influence.

size of the prize) increases. In contrast, cooperation becomes less attractive as monopoly profits increase in our framework.

The paper proceeds as follows. The next section describes a modified version of Erkal and Minehart (2008), which is appropriate for laboratory testing. In particular, the original work contains a continuous-time framework with ex-post sharing while we consider a discrete-time version of the model with ex-ante sharing. Section 3 describes the experimental design and procedures. Sections 4, 5 and 6 contain the behavioral results in the two-firm, three-firm and single-firm markets, respectively. Section 7 concludes.

2   Theoretical framework and predictions

In this section, we describe the model which is based on Erkal and Minehart (2008). They model a stochastic multi-stage R&D process where firms have to successfully complete several sequential steps of research before entering the product market. Firms cannot earn any profits before completing all of the necessary steps. Erkal and Minehart (2008) analyze when successful firms find it profitable to share their successes with lagging firms. We follow their definitions and approach. Our goal in this section is to identify the changes to their model necessary to make it suitable for direct laboratory testing without changing the general framework of the problem. The specific changes we introduce are the assumptions that (i) the discovery process and the resulting output market occur in discrete rather than continuous time, and (ii) firms sign a sharing contract before they make their investment decisions, rather than after.

Consider an environment with two firms, $i = 1, 2$. The firms invest in a research project with 2 distinct steps of equal difficulty. The steps are identical in terms of the technology and options available to the firms. Firms cannot start to work on the next step before completing the prior step and all steps need to be completed successfully before a firm can produce output.

It is assumed that each firm operates an independent research facility. Time is discrete and the firms share a common discount rate r. Firms decide at the beginning of each period

whether to invest in R&D at cost c. If a firm invests, it has a probability α of successfully completing the next step during that period. Firms learn whether or not they have been successful at the end of each period before moving onto the next period.[3] After completing a step, a firm can begin research on the next step in the next period. For a firm which has not yet completed the project, a decision not to invest the cost c is assumed to be irreversible and equivalent to dropping out of the game. Firms observe whether their rival is conducting research as well as whether the rival has a success.

We use the notation $\mathbf{h} = (h_1, h_2)$ to represent the progress made by the firms. h_i stands for the number of steps that firm i has completed and it increases by one each time firm i completes a research step. The research histories are partially ordered so that $\mathbf{h}$ is *earlier* than $\mathbf{h}'$ if and only if $h_i \leq h_i'$ for $i = 1, 2$, with strict inequality for at least one firm. Research histories where $h_1 = h_2$ and $h_1 \neq h_2$ are referred to as symmetric and asymmetric histories, respectively. If a firm has dropped out of the game, this is denoted by X in the research history.

When they make their investment decisions, firms may simultaneously decide to form a research joint venture. This involves an enforceable agreement to share the research outcomes in cases when at least one of the firms is successful. Such sharing saves the lagging firm from having to continue to invest to complete the step. To keep things simple in the experimental design, we assume that firms can sign a sharing agreement only at the symmetric histories $(0,0)$ and $(1,1)$.[4] We assume that investment decisions are not contractible, so firms still make their investment decisions independently. Moreover, sharing involves no payments, so for sharing to take place, both firms have to individually find it profitable to share their research outcomes.[5] It is assumed that the lagging firm cannot

---

[3]In contrast, Erkal and Minehart (2008) consider a continuous-time game where R&D is modelled using a Poisson discovery process.

[4]This implies that in cases when both firms are successful, there is no need to share.

[5]We assume that firms can sign a contract, but they cannot agree to make side payments to each other. This is not a crucial assumption given that we allow for sharing at symmetric histories only. In Kamien et al. (1992), this form of R&D cooperation is called 'RJV competition.' There are a variety of ways to model the sharing process. Erkal and Minehart (2008) consider licensing, where the leading firm shares its result with the lagging firm in exchange for a licensing fee. The leader makes a take-it-or-leave-it offer to the lagging firm. If the lagging firm accepts the offer, it pays the licensing fee to the leader who then shares one step

observe the technical content of the rival's research without explicit sharing. In this sense, there are no technological spillovers.

Let H denote the set of research histories. It is given by

$$H = \{((h_1, h_2), (h_1, X), (X, h_2) \text{ for } h_i = 0, 1, 2 \text{ and } i = 1, 2\}$$

We restrict attention to pure Markov strategies. A pure Markov strategy is a function on H that specifies an action for firm i at each history. At each history, the set of available actions for firm i is as follows. At asymmetric histories (h_1, h_2), where $h_1 \neq h_2$, and for the histories (h_1, X) or (X, h_2) with $h_i < 2$, active firms simultaneously decide whether or not to invest in the next step of research. An inactive firm is out of the game and so chooses no action. At $(2, 2)$, the firms earn duopoly profits while at $(2, X)$ and $(X, 2)$, the active firm earns monopoly profits. At symmetric histories (h, h) with $h < 2$, the firms simultaneously and individually decide whether they want to invest, and if they do, whether they would like to have a sharing agreement. If they decide to have a sharing agreement, the history transitions to $(h+1, h+1)$ as soon as one of the firms has a success. If they decide to invest alone, the history transitions to $(h+1, h)$, $(h, h+1)$, or $(h+1, h+1)$ depending on whether firm 1 or firm 2 or both firms have a success.

The payoffs of each firm can be described as functions of the current history and the equilibrium strategies. The equilibrium value functions $V_i(\mathbf{h})$ for $i = 1, 2$ are given by a Bellman equation. At symmetric histories such that $h < 2$, when there is no sharing agreement, the Bellman equation for firm 1 is

$$
\begin{aligned}
&V_1(h, h; NS) \\
= \ & \alpha^2 \frac{V_1(h+1, h+1)}{(1+r)} + (1-\alpha)\alpha \left(\frac{V_1(h, h+1)}{(1+r)} + \frac{V_1(h+1, h)}{(1+r)} \right) - c \\
& + \frac{(1-\alpha)^2}{(1+r)} \left(\begin{array}{c} \alpha^2 \frac{V_1(h+1,h+1)}{(1+r)} + (1-\alpha)\alpha \left(\frac{V_1(h,h+1)}{(1+r)} + \frac{V_1(h+1,h)}{(1+r)} \right) - c \\ + \frac{(1-\alpha)^2}{(1+r)} \left(\alpha^2 \frac{V_1(h+1,h+1)}{(1+r)} + (1-\alpha)\alpha \left(\frac{V_1(h,h+1)}{(1+r)} + \frac{V_1(h+1,h)}{(1+r)} \right) - c + ... \right) \end{array} \right)
\end{aligned}
$$

---

of research. Our implementation choice has several advantages in the laboratory. Take-it or-leave-it offers which result in highly unequal payoffs are often rejected in ultimatum game experiments even if they are profitable. Subjects could engage in a bargaining process, but this would be time consuming and increase the cognitive complexity of the experimental task.

where $V_1(h, h; NS)$ denotes the equilibrium value function conditional on the firms deciding not to share at (h, h). This expression simplifies to

$$
\begin{aligned}
&V_1(h, h; NS)\\
&= \left(\alpha^2 \frac{V_1(h+1, h+1)}{(1+r)} + (1-\alpha)\alpha \left(\frac{V_1(h, h+1)}{(1+r)} + \frac{V_1(h+1, h)}{(1+r)}\right) - c\right)\left(\frac{1+r}{r+2\alpha-\alpha^2}\right).
\end{aligned}
$$

At symmetric histories with sharing, the Bellman equation for firm 1 is

$$
\begin{aligned}
&V_1(h, h; S)\\
&= \alpha^2 \frac{V_1(h+1, h+1)}{(1+r)} + 2(1-\alpha)\alpha\left(\frac{V_1(h+1, h+1)}{(1+r)}\right) - c\\
&\quad + \frac{(1-\alpha)^2}{(1+r)}\left(\begin{array}{c}\alpha^2 \frac{V_1(h+1,h+1)}{(1+r)} + 2(1-\alpha)\alpha\left(\frac{V_1(h+1,h+1)}{(1+r)}\right) - c\\ + \frac{(1-\alpha)^2}{(1+r)}\left(\alpha^2 \frac{V_1(h+1,h+1)}{(1+r)} + 2(1-\alpha)\alpha\left(\frac{V_1(h+1,h+1)}{(1+r)}\right) - c + ...\right)\end{array}\right)
\end{aligned}
$$

which simplifies to

$$
\begin{aligned}
&V_1(h, h; S)\\
&= \left(\alpha^2 \frac{V_1(h+1, h+1)}{(1+r)} + 2(1-\alpha)\alpha\left(\frac{V_1(h+1, h+1)}{(1+r)}\right) - c\right)\left(\frac{1+r}{r+2\alpha-\alpha^2}\right).
\end{aligned}
$$

After a firm completes all stages of the research process, it can participate in the product market. The firms produce goods that may be either homogeneous or differentiated. If both firms have completed the research project, they compete as duopolists and each earns a per-period profit of $\pi^D \geq 0$. If only one firm has completed the research project, the firm earns a per-period monopoly profit of $\pi^M > \pi^D$ as long as the other firm does not produce output.[6]

If the firms produce homogeneous products and compete as Bertrand or Cournot competitors, then $\pi^M > 2\pi^D$. If the firms produce differentiated products, then for low levels of product differentiation, $\pi^M > 2\pi^D$ and for high levels of product differentiation, $\pi^M \leq 2\pi^D$.

As in Erkal and Minehart (2008), we carry out the analysis by dividing the parameter space into the following two regions.

Definition 1 *Region A consists of those parameter values such that in every Markov perfect equilibrium of the game, firms do not exit at any history either on the equilibrium path or off the equilibrium path. Region B consists of all other parameter values.*

---

[6]The magnitudes of π^D and π^M do not depend on the decisions taken during the research phase.

The condition for Region A is given by the following.

Lemma 1 *Region A consists of all parameters such that $\pi^D \geq c\frac{r}{\alpha}(2 + \frac{r}{\alpha})$.*

Proof. See the appendix. ∎

A lagging firm has the highest incentives to drop out when it is as far behind the leading firm as possible. Hence, the condition is given by the condition for investment at the history $(2,0)$ for firm 2.

In the experiments, we primarily restrict our attention to Region A and explore whether the equilibria satisfy the following monotonicity definition.

Definition 2 *An equilibrium satisfies the monotonicity property if whenever the firms share at the history (h', h'), then they also share at the earlier history (h, h), where $h < h' \in \{0, 1\}$.*

In Region A, the following result holds.

Proposition 1 *In Region A, every MPE sharing pattern is monotonic.*

Proof. See the appendix. ∎

This result implies that a decision not to share is never followed by a decision to share in Region A. The sharing conditions specified in equations (9), (14) and (15) in the appendix imply that, holding everything else constant, as π^M increases, the incentives to share decrease. Proposition 1 implies that as π^M increases, sharing breaks down in later stages before it breaks down in earlier stages.

As shown in the proof of Proposition 1, when the sharing condition at $(1,1)$ holds, there exist multiple equilibria. Since sharing requires both parties to opt into the joint venture, a firm is indifferent between choosing to share or not to share as long as its opponent chooses not to share. As a result, in one equilibrium, both firms choose to share and in the other equilibrium, neither firm chooses to share. The two equilibria can be Pareto ranked and the sharing equilibrium yields strictly higher profits to both firms. Similarly, when the sharing condition at $(1,1)$ does not hold, there exist multiple equilibria. In one equilibrium, neither

firm chooses to share. In the other two equilibria, one firms chooses to share and the other one chooses not to share. However, since sharing requires both firms to agree to it, the firms do not share. Hence, the outcome is the same in both equilibria.

Erkal and Minehart (2008) demonstrate that the monotonicity property may be violated in Region B. They show that for an open set of parameters in this region, there is a Markov perfect equilibrium such that the firms share at $(2, 1)$ but not at $(1, 0)$, where both histories arise on the equilibrium path. Since the parameter values we focus on in the experiments are predominantly such that no lagging firm has an incentive to drop out at any point in the race, we do not discuss equilibrium behavior in Region B and refer the reader to their paper for insights. In order to observe how drop-put behavior is affected in the laboratory, we consider in only one of the markets parameters such that, according to the theoretical prediction, a firm drops out as soon as it falls behind in the research process. In this market, the parameters are chosen such that the condition for dropping out at $(2, 1)$, given by $V_2(2, 1) = \frac{(1+r)(\alpha\tilde{\pi}^D - c)}{(\alpha + r)} < 0$, is satisfied.[7] This is because a lagging firm has the lowest incentives to drop out at $(2, 1)$ or $(1, 2)$. That is, if the lagging firm drops out at $(2, 1)$ or $(1, 2)$, the lagging firm drops out at all other asymmetric histories.

3 Experimental design and procedures

The experiments utilize a within-subjects design to evaluate the predictive success of the model. All of them were conducted at the University of Melbourne. Each subject was in the role of a firm deciding on the optimal R&D strategy under a variety of market parameters. Subject incentives were aligned with those of the firms described in the theoretical model as subjects were paid in cash at the end of the experiment based on their profits. They were paid at the rate of 100 experimental earnings = AUD\$1. The average salient payment was AUD\$42.2.[8]

Two additional aspects of the theoretical model needed to be considered before imple-

---

[7] This expression is derived in the proof of Lemma 1 in the appendix. The condition for dropping out at $(1, 2)$ is the same.

[8] This payment was for about two hours. It is approximately equal to US\$39.74 based on the prevailing exchange rate when the experiments were conducted.

menting it in the laboratory. First, the model considers an infinite-horizon problem with a discount rate r. To handle this, a random stopping rule was implemented. Subjects were told that each market would end after each period with probability δ, which was public information. For a given value of r, δ was set equal to $\delta = 1/(1 + r)$.[9] The random stopping rule prevented us from following the typical practice of recruiting subjects for a fixed amount of time. For this reason, prior to the sessions, the student subjects were told that the experiment was expected to last about two hours, but that it had a random stopping rule and hence there was a small chance that the experiment would not finish in two hours. To further emphasize this feature, every session began in late afternoon, after regular classes ended.

The second issue to be considered pertained to the investment cost. The theoretical model specifies that a firm invests c each period during the R&D process as long as it is active and earns 0 if it drops out of the R&D race. Institutional controls prevent subjects from leaving the laboratory with negative earnings. The requirement that subjects walk away with at least $0 meant that those subjects with negative earnings would always invest since they would not bear the costs but might reap some benefit. Thus, investment costs created the potential for loss of experimenter control. The standard technique to handle this is to endow subjects with a budget (a transfer from the experimenter) from which costs can be deducted (paid). However, in this case the number of periods in which a subject may invest is stochastic and thus regardless of how large the endowment is, there is a chance that the subject will end up with a negative payoff.[10] To handle this issue, the investment cost was framed as an opportunity cost. Subjects earned 0 while engaging in R&D, but earned c per period if they chose to not develop the product. This change necessitates that the profits from successful completion of the R&D process, as stated in Section 2, be increased by c as well.

Each session consisted of 20 markets as shown in Table 1. The first 5 markets in every

---

[9] This is a common approach used in laboratory experiments. See Charness and Genicot (2006) for a discussion.

[10] Alternatively, one could simply force the subject to stop development once the budget is exhausted, but this fundamentally changes the decision problem.

session involved only a single firm, which allowed the subjects to become familiar with the computer interface and allowed us to measure risk attitudes.[11] Markets 6 through 10 involve two firms in a two-step process, the main focus for this paper. These environments are repeated in markets 16 through 20. Markets 11 through 15 increase either the number of steps to four (markets 11 through 13) or increase the number of firms to three (markets 14 and 15). These markets are conducted for two reasons. First, such markets exploit the opportunity that the laboratory offers to explore beyond the domain of developed theory. Second, these markets serve as a distraction for the subjects between markets 6 through 10 and their replication in the final five markets.

In Table 1, π^M, π^D and π^T stand for the monopoly, duopoly and triopoly profits in the product market as observed by the subjects. Given that investment costs were implemented as an opportunity cost, these profits differ from those described in the previous model by an amount c. For example, market 6, which has an opportunity cost and profits of $c = 10$, $\pi^M = 120$, and $\pi^D = 30$ in Table 1, corresponds to an environment with an investment cost and profits of $c = 10$, $\pi^M = 120 - 10 = 110$, and $\pi^D = 30 - 10 = 20$ in the theoretical discussion. JV @ (h, h) and DP @ (h, h) indicate the predicted outcomes of forming a joint venture or developing privately at the history (h, h), respectively. In cases when the market is exploratory, we use "?" to denote that no a priori hypotheses exist.

The predictions for markets 6 through 10, and 16 through 20 follow directly from the previous section. All of the parameter choices, except for markets 9 and 19, fall in Region A. In markets 9 and 19, a firm should drop out if it is ever behind given the minimal difference between c and π^D. Markets 11 through 13 are similar to markets 10, 6 and 8, respectively, except that the number of steps is greater.[12] These markets serve as a robustness check on

---

[11]Assuming a constant relative risk aversion utility function of the form $u(x) = \frac{x^{(1-\gamma)}}{(1-\gamma)}$ where $u(0) = 0$, the decision to develop privately implies that $\frac{c^{(1-\gamma)}}{[(1-\gamma)(1-\delta)]} < \frac{\alpha\delta(\Pi^M)^{(1-\gamma)}}{[(1-\gamma)(1-\delta)(1-\delta+\delta\alpha)]}$. The parameters choices for markets 2 through 5 place bounds on the degree of risk aversion similar to those used by Holt and Laury (2002). Undertaking R&D in markets 2, 3, 4, and 5 indicates that a subject is more risk loving than $\gamma = -0.16$, $+0.15$, $+0.42$, and $+0.68$, respectively. As these are the first markets in which the subjects participated, if there is a learning effect, then this measure of risk attitude is noisy.

[12]The parameters for the two-step, two-firm markets were chosen such that they fall within the bounds of Region A in the four-step, two-firm markets. In a four-step process, the follower will have the highest incentives to drop out at the history $(4, 0)$ or $(0, 4)$. The condition on duopoly profits is given by $\pi^D >$

10

Table 1: Experiment parameters by market

Market	# of firms	# of steps	δ	α	c	π^M, π^D, π^T	Hypotheses
1	1	3	0.9	0.75	1	10	–
2	1	1	0.5	0.9	11	21	DP if $\gamma < -0.16$
3	1	1	0.5	0.7	7	20	DP if $\gamma < 0.15$
4	1	1	0.5	0.8	5	20	DP if $\gamma < 0.42$
5	1	1	0.8	0.5	5	18	DP if $\gamma < 0.68$
6	2	2	0.9	0.4	10	120, 30	DP @ $(0,0)$ and $(1,1)$
7	2	2	0.9	0.4	10	80, 30	JV @ $(0,0)$, DP @ $(1,1)$
8	2	2	0.9	0.4	10	40, 30	JV @ $(0,0)$ and $(1,1)$
9	2	2	0.9	0.4	10	120, 12	ND if behind
10	2	2	0.9	0.4	10	200, 30	DP @ $(0,0)$ and $(1,1)$
11	2	4	0.9	0.4	10	200, 30	DP @ $(2,2)$ and $(3,3)$
12	2	4	0.9	0.4	10	120, 30	DP @ $(2,2)$ and $(3,3)$
13	2	4	0.9	0.4	10	40, 30	JV @ $(2,2)$ and $(3,3)$
14	3	3	0.9	0.4	10	120, 110, 30	?
15	3	3	0.9	0.4	10	120, 40, 30	?
16	2	2	0.9	0.4	10	120, 30	DP @ $(0,0)$ and $(1,1)$
17	2	2	0.9	0.4	10	80, 30	JV @ $(0,0)$, DP @ $(1,1)$
18	2	2	0.9	0.4	10	40, 30	JV @ $(0,0)$ and $(1,1)$
19	2	2	0.9	0.4	10	120, 12	ND if behind
20	2	2	0.9	0.4	10	200, 30	DP @ $(0,0)$ and $(1,1)$

the two-step markets given the monotonicity property. Note that if the two firms in market 11 have both completed the first two research steps, they are in the same strategic position as the two firms in market 10 that have not completed any steps. Therefore, the prediction for the last two research steps in market 11 is the same as that for market 10. Markets 12 and 6, and 13 and 8 are matched in a similar way.

Erkal and Minehart (2008) show that the results from the two-step analysis extend to the case of three steps in a straightforward fashion. Although they do not have equilibrium results for a research process with an arbitrary number of steps, they argue, by considering a related problem, that the monotonicity result holds more generally.[13] Based upon their findings, we intuitively expect that firms should cooperate throughout market 13 since they are expected to cooperate at the last two steps. Further, we expect firms to be at least as cooperative in market 12 as they are in market 11, given the higher monopoly profits they can earn in market 11.

Markets 14 and 15 are three-firm markets. There are several ways to implement a joint venture with more than two firms. We chose to allow subjects to either agree or not agree to be in a joint venture at any point in the game when there was at least one other subject which had the same number of successes as them. At the symmetric histories $(0,0,0)$, $(1,1,1)$ and $(2,2,2)$, the size of the joint ventures depended on the number of subjects who agreed to be part of them. At these histories, the subjects could not indicate a desire to be in a joint venture with only one of their rivals.[14]

The predictions for markets 14 and 15 are less clear. The two parameter sets we have chosen differ in terms of the duopoly profits. In market 14, duopoly and monopoly profits are similar, and intuitively one may expect to see two firms select JV if they are further

$c\frac{r}{\alpha}\left[4 + 6\frac{r}{\alpha} + 4\left(\frac{r}{\alpha}\right)^2 + \left(\frac{r}{\alpha}\right)^3\right]$. Hence, as the number of research steps increase, the follower needs to have higher duopoly profits to stay in the race.

[13]See section 5 in their paper. They do not fully consider the case of a research process with N steps because the analysis becomes too cumbersome.

[14]An advantage of this approach is that it was easy to implement. It did not require us to give directions to the subjects which are specific to the three-firm markets. This was undesirable because the subjects were going to participate in more two-firm markets and could get confused between the protocols for the different types of markets.

along in the innovation process than the third. In market 15, where duopoly profits are close to triopoly profits, one may expect to see two firms forming a joint venture if they are behind in the research process.

A total of 96 subjects participated in the 8 laboratory sessions.[15] Each session consisted of exactly 12 subjects, which was announced to the participants, and two sessions were conducted concurrently. To control for sequencing effects, the order in which the markets shown in Table 1 were presented to the subjects varied across the sessions.[16] To minimize repeated play effects, subjects were randomly and anonymously placed into groups for each market involving more than a single firm.

In the laboratory, subjects were seated at individual workstations. Privacy dividers ensured that subjects could not see each other. The written directions were self paced and subjects completed a comprehension handout after finishing the directions.[17] Before the actual experiment began, the experimenters checked the answers of each participant, answered any remaining questions, and read aloud the summary points which appeared at the end of the directions.

The actual experiments were computerized. Figure 1 shows an example screen image. The task was presented to subjects with similar terminology to that used in the model presented above. This context serves to aid the subjects in understanding what is a fairly complicated task.[18] In the top middle section of the screen, subjects made the decision to "Not Develop (ND)" a new product (and simply sell the old product), pursue the new product solo by selecting "Develop Privately (DP)," or pursue it as part of a "Joint Venture

---

[15] Participants were drawn from the laboratory's pool of undergraduate students. Some of the subjects had previously participated in unrelated economics experiments.

[16] Four market orderings were used with two replicates of each. In half of the sessions, the order of the five two-firm and two-step markets was reversed and in two sessions the ordering of the five exploratory markets was reversed. Let A denote markets 6-10 and 16-20 in the order shown in Table 1 and let a denote the reverse of this order. Let B and b stand similarly for markets 11-15. The four orderings were ABA, AbA, aBa, and aba.

[17] Copies of the directions and the comprehension handout are available upon request.

[18] In some instances, researchers prefer to use a neutral framing so as not to influence behavior. This practice is most common in experiments involving other regarding preferences such as ultimatum and public goods games. However, the use of a market context is common in market experiments where buyers and/or sellers behavior is explicitly being studied.
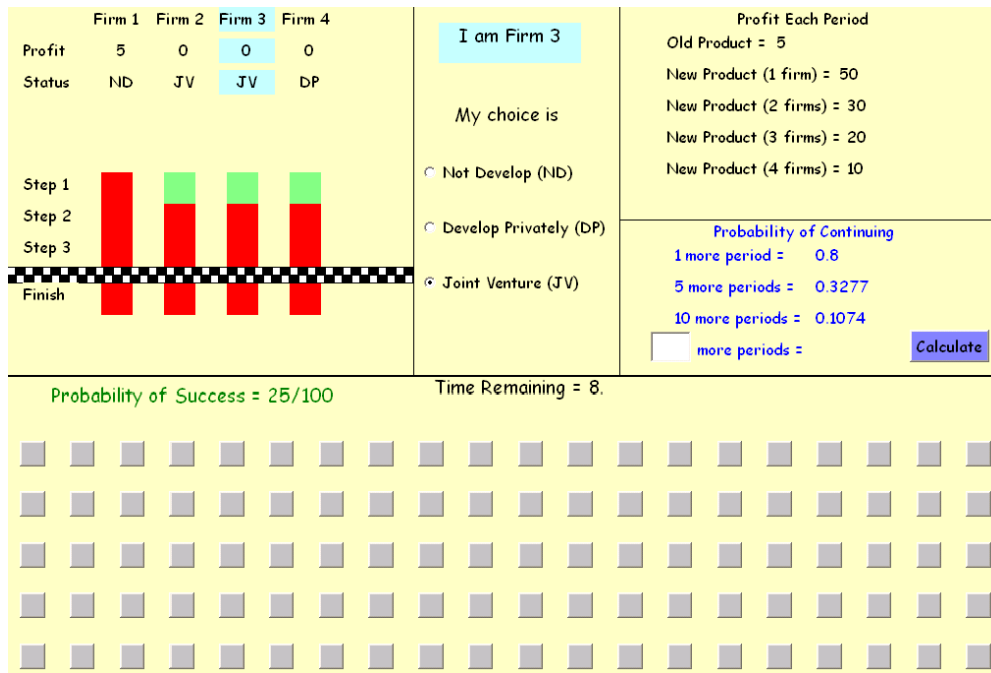
Figure 1: An example screen image

(JV)." Subjects did not earn any profit while developing the new product. If a subject opted ND, that subject earned the profit from the "Old Product" in all remaining periods of the market.[19] The per-period profit from successfully completing the R&D process depended on the number of firms who had completed development by the start of a period. This information was given on the right-hand side of the screen. The bars on the left-hand side of the screen indicated the remaining number of steps needed to complete development. Green steps (appearing in light gray shading in Figure 1) represented successful completion and red steps (appearing in dark gray shading in Figure 1) stood for the incomplete portion of the research process. The current action of each firm was shown above each bar.

At the start of each market subjects had unlimited time to make the initial development decision. Any subjects who selected either JV or DP was then presented with 100 gray boxes at the bottom of the screen. Subjects had 8 seconds to click on a single box. If the selected

---

[19]Subjects could change between JV and DP, but, consistent with the theoretical model's assumptions, once they selected ND, they were forced to select ND in all of the remaining periods of a market.

box turned green, the subject successfully completed the step and if it was red, the step was not completed. A fraction α of the boxes would turn green and $1 - \alpha$ would turn red. The locations of the green boxes were determined randomly in each period. Failure to select a box was equivalent to having selected a red box. Subjects who selected DP had to select a green box to complete the step. Subjects who selected JV completed a step when either they found a green box or someone else who selected JV and was working on the same step found a green box. After each period, the computer randomly determined whether the market continued. If the market continued, the screens were updated to reflect any progress in the previous period and subjects had 8 seconds to make a choice between ND, DP, and JV for the current period, if appropriate. If the market did not continue, subjects observed the parameters for the next market and again had unlimited time to make the initial development decision. At the conclusion of the session, subjects were paid their earnings and dismissed from the laboratory.

4 Behavioral results in the two-firm markets

Subsection 4.1 evaluates the effect of the distribution of profits on the decision to cooperate and form a joint venture in the basic two-step, two-firm markets. The cooperation incentives in the longer four-step, two-firm markets are discussed in subsection 4.2.

4.1 Behavior in the two-step, two-firm markets

Subjects made decisions in the two-step, two-firm markets twice, once in markets 6 through 10 and again in markets 16 through 20. Figure 2 shows the percentage of subject pairs forming a joint venture at each symmetric history relative to the total number of pairs that actually reached that history in markets 16 through 20. In the first four markets shown in the figure (markets 18, 17, 16 and 20), the duopoly profits were the same. These markets are ordered according to increasing monopoly profits. In the last market shown in the figure (market 19), duopoly profits were lower (12 instead of 30). In the figure, the gray bars show the behavior at $(0,0)$ and the white bars show the behavior at $(1,1)$. The
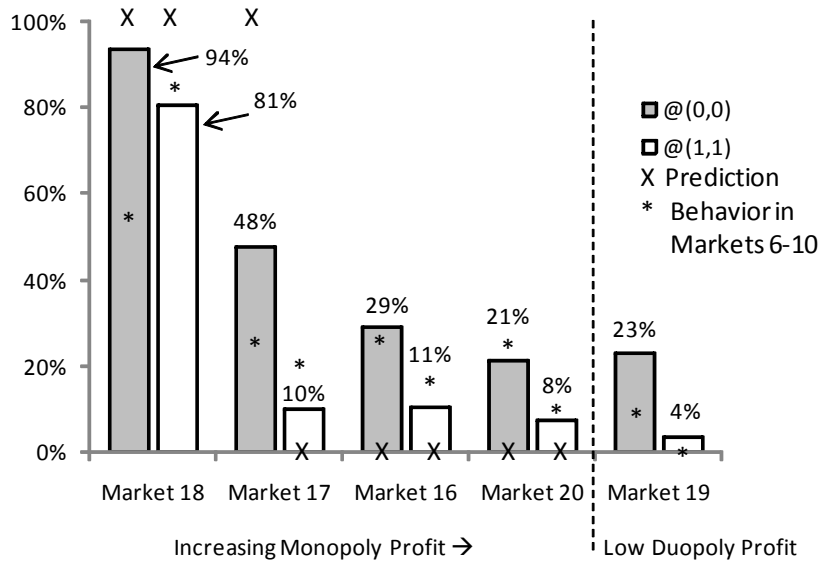
Figure 2: Percentage of pairs forming a JV in the two-firm, two-step markets

theoretical predictions are shown with an "X" while behavior in markets 6 through 10 are shown with a "*" for the corresponding parameters. The behavior was qualitatively similar between the two replications although there are some indications of a learning effect. Most notably, in markets 18 and 17, the likelihood of forming a joint venture at $(0, 0)$ increased with repetition, which is a movement towards the theoretical prediction. Because of this adjustment, the later markets serve as the basis for the discussion in this section.

Overall, the descriptive results are in line with the theoretical predictions. JVs form less frequently the closer the firms are to the final market and the greater the monopoly profits. The three instances where JVs are expected to be formed have the highest observed rates of formation. Specifically, in market 18, the duopoly and monopoly profits are similar and, as shown in Table 1, the two firms are expected to form a joint venture at every step of the process. This is essentially what is observed. Figure 2 shows that at the history $(0, 0)$, 94% of the pairs formed a joint venture in market 18 (97% of the subjects were willing

to form a joint venture). At the history $(1, 1)$, after the completion of the first step, the percentage of pairs forming joint venture fell to 81% (88% of subjects were willing to form a joint venture). Market 17 differs from market 18 in that monopoly profits are increased from 40 to 80. Here, the prediction is that firms will form a joint venture initially, but that this will break down after the completion of step 1. As monopoly profits increase, the incentives to cooperate and form a joint venture unravel earlier in the R&D process. This is the pattern that was observed. 48% of the pairs formed a joint venture at $(0, 0)$ (68% of the subjects chose to cooperate) and only 10% of the pairs formed a joint venture at $(1, 1)$ (36% of the subjects were willing to cooperate). Monopoly profits increase still further in markets 16 and 20, and as a result no cooperation is predicted in these markets. Figure 2 shows that the observed rates of joint venture formation were the lowest in these markets (29% and 11% at the two symmetric histories in market 16, and 21% and 8% in market 20). These cooperation rates are higher than predicted, but they are very low in comparison to the other markets where joint ventures are expected to form according to the theoretical predictions.

These observations are consistent with the findings from a probit model with subject and session random effects, where individual choices at symmetric histories are the unit of observation. This regression analysis accounts for the fact that observations from the same subject are not independent, nor are the observations from the same session. Subjects within the same session were rematched across different markets in order to reduce issues associated with repeated games. The regression analysis relies upon individual choices since the theoretical model is about individual firms' incentives and using pair data does not fully exploit the available information. However, the qualitative conclusions essentially remain unchanged if the analysis is performed using pair data instead of individual data.

The random effects probit model estimation results are shown in Table 2.[20] Completed1 is a dummy variable for a subject making a decision at $(1, 1)$ while the baseline is $(0, 0)$. M80+ is a dummy variable for markets in which monopoly profits are increased to at least

---

[20] The model was estimated in R using the routine of Bailey and Alimadhi (2007).

Table 2: Multivariate Regression Results - Two-firm, Two-step Markets

	Estimate	Std. Error	z-statistic	p-value
Constant	1.70	0.19	9.13	< 0.001
Completed1	-0.48	0.22	-2.20	0.028
M80+	-1.16	0.21	-5.61	< 0.001
M120+	-0.58	0.16	-3.60	< 0.001
M200	-0.05	0.16	-0.30	0.763
Completed1*M80+	-0.46	0.28	-1.67	0.095
Completed1*M120+	0.02	0.25	0.07	0.943
Completed1*M200	0.22	0.26	0.85	0.396

80, while M120+ and M200 are dummies for markets in which monopoly profits are at least 120 and equal to 200, respectively. For example, observations from market 16 (where monopoly profits are 120) have M80+ = 1, M120+ = 1, and M200 = 0. Each coefficient identifies the additional effect of an increase in monopoly profits. The remaining variables are interaction variables.

The negative and significant coefficient on M80+ indicates that subjects are less willing to form a joint venture at $(0,0)$ when monopoly profits are increased from 40 to at least 80. The negative and significant coefficient on M120+ indicates that willingness to form a joint venture at $(0,0)$ is even lower when profits are increased beyond 80. However, the coefficient on M200 indicates that there is no statistically significant change in the willingness to form a joint venture when monopoly profits are increased from 120 to 200.

To investigate the effect of increasing monopoly profits at $(1,1)$, note that the negative and significant (at the 10% level) coefficient on Completed1*M80+ indicates that an increase in monopoly profits to at least 80 leads to an even lower willingness to form a joint venture at $(1,1)$ than at $(0,0)$. The coefficients on Completed1*M120+ and Completed1*M200 are not statistically significant, which indicate that further increases in monopoly profits do not further reduce the willingness to form a joint venture at $(1,1)$ (as compared to the effects these changes have at $(0,0)$). Taken together, these results indicate that as monopoly profits increase, subjects are less willing to form a joint venture.

We next analyze how making progress in the innovation process (i.e., moving from $(0,0)$

to $(1, 1)$) affects the incentives to form a joint venture. The negative and significant coefficient on Completed1 demonstrates that when monopoly profits are 40, subjects are less willing to form a joint venture at $(1, 1)$ than at $(0, 0)$. As mentioned previously, the negative and significant coefficient on Completed1*M80+ indicates that the negative effect of progress is even larger when monopoly profits are at least 80. However, since the coefficients on Completed1*M120+ and Completed1*M200 are not significant, the difference between the incentives at $(0, 0)$ and $(1, 1)$ does not continue to grow as monopoly profits are increased further. Taken together, these results suggest that subjects are less willing to form a joint venture the closer they are to the product market.

The duopoly profits in market 19 were lower than they were in the other two-firm, two-step markets. For market 19, the theoretical predictions are that firms do not form a joint venture and any firm that finds itself behind its rival drops out of the race. Figure 2 shows that behavior in market 19 is similar to that observed in markets 16 and 20 in terms of the formation of joint ventures. However, there were dramatically more drop-outs in market 19, as expected. In fact, 14 firm pairs out of a possible 48 had a firm drop out in market 19 while only 10 drop-outs occurred in markets 16, 17, 18, and 20 combined. The difference in the drop-out rates between markets 19 and each of the other four markets was significant (p-value = 0.016, 0.063, 0.008, and 0.063 for markets 16, 17, 18, and 20, respectively).[21] Of the 14 drop-outs in market 19, 11 occurred when the lagging firm was only one step behind its rival.

4.2   Behavior in the four-step, two-firm markets

In the four-step markets, we continue to focus on Region A, where the follower does not have incentives to drop out of the race. The four-step markets use the same parameters as three of the two-step markets discussed above (markets 16, 18 and 20). Therefore, if a four-step market reaches a situation in which both firms have completed the first two steps, then behavior in the last two research steps should be the same as in the corresponding

---

[21]The p-values are based on a sign test using the change in the percentage of drop-outs between market 19 and the other market in a session.

two-step market.

Figure 3 plots the percentages of subject pairs forming a joint venture at each symmetric step in the four-step markets. Monopoly profits were 40, 120 and 200 in markets 13, 12 and 11, respectively. Behavior in the two-step markets under the same parameterization are shown with a "+."

From Table 1, the prediction for market 13 is that the subjects would form joint ventures at the histories $(2,2)$ and $(3,3)$. Figure 3 shows that cooperation is quite high in this market. The lowest rate of joint venture formation was 71%, observed in the very first step. This rate is low due to the 15 subjects who dropped out of the race immediately at $(0,0)$. In general, the pattern in the last two steps is similar to, although slightly lower than, the rates observed in market 18.

Table 1 indicates that we would not expect subjects to form any joint ventures at the histories $(2,2)$ and $(3,3)$ in markets 11 and 12. Figure 3 shows that, as expected, cooperation levels are quite low at the history $(3,3)$ in these two markets. Moreover, they are close to the cooperation levels at the history $(1,1)$ in markets 16 and 20 (where the monopoly profits are 120 and 200, respectively). However, cooperation is quite high at the history $(2,2)$ and higher than what it is at the history $(0,0)$ in markets 16 and 20.

Table 3 presents the results from the regression analysis. We again estimated a random effects probit model using individual level data. In Table 3, Completed1, M120+ and M200 have the same meaning as they do in Table 2. The baseline case is a decision at the history $(0,0)$ when monopoly profits are 40. Completed2 and Completed3 are dummy variables for decisions made at the histories $(2,2)$ and $(3,3)$, respectively. 2Steps is a dummy variable for observations from two-firm, two-step markets. These observations are included to compare behavior in the last two stages of the four-step markets (at $(2,2)$ and $(3,3)$) with those in the two-step markets (at $(0,0)$ and $(1,1)$, respectively). Such a comparison is possible since according to the theoretical model, equilibrium strategies depend on the remaining number of steps and product market parameters.[22]

---

[22]Only markets with the same profit parameters as the four-step markets are considered in the regression analysis.
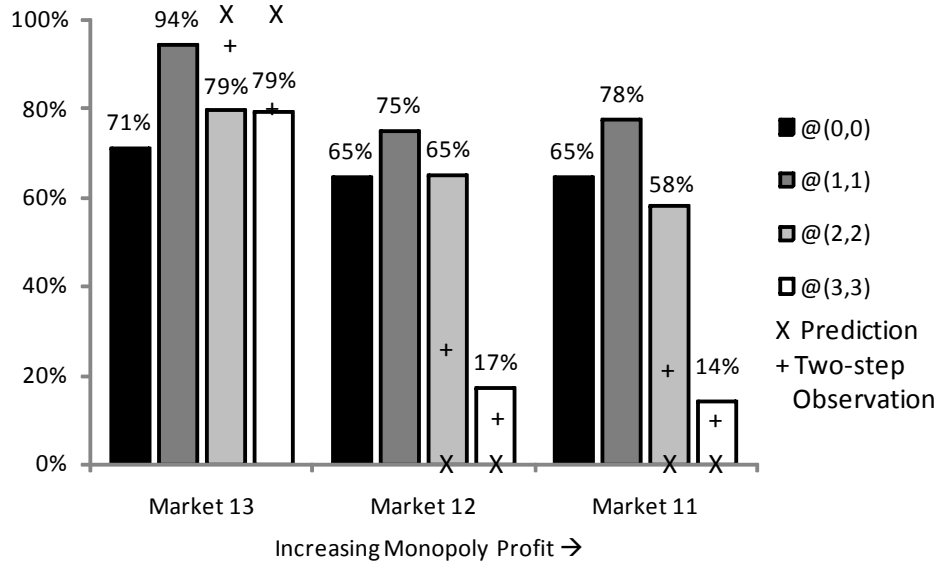
Figure 3: Percentage of pairs forming a JV in the two-firm, four-step markets

Table 3: Multivariate Regression Results - Two-firm, Four-step Markets

	Estimate	Std. Error	z-statistic	p-value
Constant	0.98	0.15	6.48	< 0.001
Completed1	0.93	0.33	2.80	0.005
Completed2	0.28	0.23	1.22	0.224
Completed3	0.41	0.25	1.65	0.099
M120+	−0.33	0.18	−1.84	0.066
M200	−0.03	0.17	−0.20	0.845
Completed1*M120+	−0.57	0.38	−1.52	0.129
Completed1*M200	−0.10	0.26	−0.37	0.709
Completed2*M120+	−0.11	0.29	−0.38	0.701
Completed2*M200	−0.23	0.26	−0.89	0.372
Completed3*M120+	−1.58	0.31	−5.15	< 0.001
Completed3*M200	0.09	0.27	0.35	0.730
2steps*M120+	−0.23	0.32	−0.70	0.484
2steps*M200	0.12	0.30	0.42	0.677
2steps*Completed2	0.28	0.25	1.14	0.256
2steps*Completed3	−0.31	0.25	−1.25	0.212
2steps*Completed2*M120+	−1.04	0.44	−2.36	0.018
2steps*Completed2*M200	0.09	0.39	0.23	0.819

21

We first consider the effects of increasing monopoly profits in markets with four steps. The negative and significant coefficient on M120+ indicates that subjects are less willing to form a joint venture at $(0,0)$ when monopoly profits are at least 120. However, a further increase in monopoly profits does not further change the willingness to form a joint venture, as shown by the coefficient on M200. Since the coefficients of the interaction variables Completed1*M120+ and Completed1*M200 are not statistically significant, increasing monopoly profits at $(1,1)$ to at least 120 or 200 has no impact on the willingness to form a joint venture beyond the impact these variables have at $(0,0)$. A similar conclusion can be reached for $(2,2)$ by looking at the coefficients on the interaction variables Completed2*M120+ and Completed2*M200. In contrast, at $(3,3)$, monopoly profits do have an additional impact on the willingness to form a joint venture. In markets where monopoly profits are at least 120, subjects are even less willing to form a joint venture at $(3,3)$ as compared to earlier histories, as evidenced by the negative and significant coefficient on Completed3*M120+. However, at $(3,3)$, there is no additional reduction in the willingness to cooperate if monopoly profits are increased from 120 to 200 since the coefficient on Completed3*M200 is insignificant.

To evaluate the impact of making progress in the innovation process, we first consider the case of low monopoly profits. The positive and significant coefficient on Completed1 indicates that subjects are more willing to form a joint venture at $(1,1)$ than at $(0,0)$ when monopoly profits are 40. The coefficients on Completed2 and Competed3 indicate that there is no statistically significant difference in the willingness to form a joint venture between the histories $(1,1)$ and $(2,2)$, but, moving from $(2,2)$ to $(3,3)$, there is a statistically significant decrease in the willingness to form a joint venture. Monopoly profits of at least 120 do not result in different progress effects from those identified for the low-profit markets when comparing the histories $(0,0)$ and $(1,1)$, or the histories $(1,1)$ and $(2,2)$, as evidenced by the coefficients on Completed1*M120+ and Completed2*M120+. However, moving from $(2,2)$ to $(3,3)$, there is a significant decrease in the willingness to form a joint venture when profits are at least 120 as compared to the low-profit markets.[23] The coefficients

---

[23]In markets where monopoly profits are low, there is more cooperation at $(3,3)$ than at $(2,2)$ while in markets where monopoly profits are at least 120, there is less cooperation at $(3,3)$ than at $(2,2)$. Completed3

on Completed 1*M200, Completed2*M200 and Completed3*M200 indicate that increasing monopoly profits from 120 to 200 does not have a significant impact on the step-by-step effect of progress.

Among the interaction terms which include the 2Step dummy variable, the only one that is significantly different from zero is 2Step*Completed2*M120+, which is negative. These results indicate that in both the four-step and two-step markets, behavior in the last step (i.e., at the histories $(3,3)$ and $(1,1)$) is the same at all three profit levels. Furthermore, conditional on history, there is no difference between the four-step and two-step markets with monopoly profits of 40 since the coefficients on 2Step*Completed2 and 2Step*Completed3 are not statistically different from zero. However, the coefficients on 2Step*Completed2*M120+ and 2Step*Completed2*M200 indicate that behavior at the penultimate step differs between the two-step and four-step markets when monopoly profits are at least 120 and that this difference is not affected by increasing monopoly profits from 120 to 200.

It is also worth noting that although we have picked our parameters such that there would be no drop-out in the four-step markets, the drop-out rates were very high. However, the drop-out rates decreased as monopoly profits increased in these markets.[24] Only a single firm dropped out in market 11 while 11 firms did in market 12, and 21 firms did in market 13. The vast majority of drop-outs occurred immediately or once a firm was behind by a single step.

5 Behavioral results in the three-firm markets

In markets 14 and 15, we explored environments with three firms and three steps, for which we do not have theoretical predictions. As explained above, in these markets, the subjects decided whether to be part of a joint venture whenever they were in a situation where at least one of their rivals had the same number of successes as them. At the symmetric

---

+ Completed3*M120+, which represents the total effect at $(3,3)$, is negative.

[24]This apparent reaction by subjects to monopoly profits is in contrast with the theoretical prediction. The drop-out condition given above does not depend on the monopoly profits.

histories $(0, 0, 0)$, $(1, 1, 1)$ and $(2, 2, 2)$, the subjects were not allowed to indicate a desire to be in a joint venture with only one of their rivals.

Given the exploratory nature of these markets, we focus our discussion on the descriptive results. Figure 4 shows how often joint ventures involving two and three firms were formed at the symmetric histories in markets 15 and 14. In both markets, monopoly profits were 120. In market 15, duopoly profits were 40 while in market 14, they were 110. It seems intuitive to expect more joint ventures to be formed in market 14 once two firms were at least one step ahead of the third one. Unfortunately, there is little evidence to support or contradict this conjecture due to the high cooperation rates observed both at $(0, 0, 0)$ and $(1, 1, 1)$, implying that very few groups made decisions at asymmetric histories such as $(1, 1, 0)$.

The general pattern that emerges from Figure 4 is that although the willingness to form joint ventures was high at all symmetric histories, there was a decline in this willingness at $(2, 2, 2)$. In both markets, less groups chose to form a joint venture at $(2, 2, 2)$ and more of the joint ventures formed involved two subjects rather than three (which indicates that one of the subjects chose not to be involved). The fact that there is a decline in the willingness to form joint ventures as the subjects approach the product market is consistent with our results from Sections 4 and 4.2.

Without explicit theoretical predictions, we make no further judgment on performance. It is tempting to conclude that subjects are mainly focusing on the best (monopoly) and worst (triopoly) outcomes possible since the cooperation rates do not seem to depend on duopoly profits. However, there were 7 drop-outs in market 15 where duopoly profits were 40, and there was only one drop-out in market 14 where duopoly profits were 110.

6   Behavioral results in the single-firm markets

Both the higher than predicted cooperation rates observed in the markets where firms are expected to develop privately, and the drop-out behavior observed in markets 12 and 13 are suggestive of risk aversion. Markets 2 through 5 involve a single firm in a one-step problem
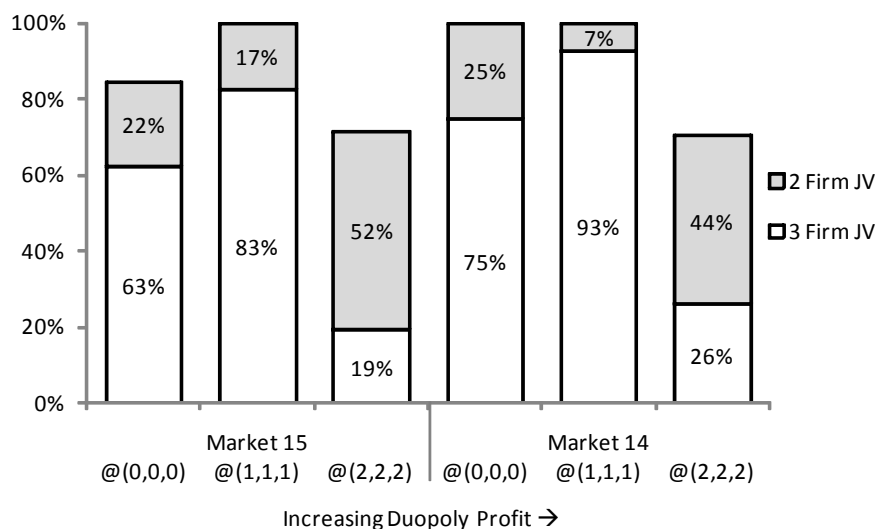
Figure 4: Percentage of groups forming a JV in the three-firm, three-step markets

and can be used to measure the subjects' degree of risk aversion.[25] Table 3 shows the results of this analysis assuming a CRRA utility function for the subjects in the experiment and compares the observed behavior to the results reported in Holt and Laury (2002). Clearly, Table 3 shows that few subjects act as though they are risk averse and, in fact, many appear to be risk loving. These results differ from the ones in most of the previous laboratory studies (e.g., Holt and Laury, 2002) which report that subjects are typically risk averse.

One must be cautious in interpreting the single-firm results. First, 17% of the subjects did not behave in a consistent manner across these four markets.[26] These markets were always introduced first, in part to help the subjects gain experience before they made their decisions in the more complicated multi-firm markets which are the primary focus of this

---

[25] Market 1 also involves a single firm and, as such, can also be used to measure risk. However, since it was designed to introduce the subjects to the interface, it involves multiple steps which makes the analysis less straightforward.

[26] All but one of the inconsistent subjects would have been consistent had one of their choices been reversed. Holt and Laury (2002) also report that some subjects were not consistent in their experiments even though the task presented in their study is a much simpler one.

Table 4: Distribution of implied degree of CRRA for consistent subjects

Parameter Range	$(\infty, -0.16]^{+}$	$(-0.16, 0.15]$	$(0.15, 0.42]^{++}$	$(0.42, 0.68]$	$(0.68, \infty]$
Current Study	0.76	0.15	0.06	0.03	0
Holt and Laury (2002)	0.08	0.26	0.26	0.23	0.17

$^{+}$ The parameter range identified by Holt and Laury (2002) was at -0.15.
$^{++}$ The parameter range identified by Holt and Laury (2002) was at 0.41. To generate the exact boundary in the current study would require the probability parameters to be specified with greater precision (i.e., more than a single decimal), which could increase the complexity perceived by the subjects.

study. Therefore, subject confusion could be driving some of the inconsistent behavior in these early markets. Also, subjects may be willing to take risks in the single-firm markets early in the experiment to gain experience which they believe could be beneficial in later markets.[27]

Two additional considerations are that subjects may be biased towards choosing to develop a new product as they feel obligated to participate in a market given that they are being paid by the experimenters to be in the study or that they may simply derive utility from "playing the game" as opposed to watching their profits accumulate.[28] However, utility from playing the game should bias down the formation of joint ventures in the multi-firm markets. On the contrary, higher cooperation rates than predicted were observed. Moreover, a perceived obligation to participate in a market should bias behavior away from not developing. However, more drop-outs than predicted were observed.[29]

7 Conclusion

We have analyzed, using laboratory experiments, the dynamics of sharing incentives in a multi-stage R&D model based on Erkal and Minehart (2008). Our results are in general

---

[27] While subjects did not know how many markets would be run during the experiment, they knew, when they were making their decisions in the initial markets, that they would be participating in multiple markets and that the experiment was expected to last for at least another hour.

[28] The subjects did not earn any profits while engaging in R&D, but they did earn profits when they chose not to develop.

[29] For example, ND was observed 55 times in markets 6 though 10.

consistent with the theoretical predictions for the two-step, two-firm markets with no drop-out. We have shown that as monopoly profits increase in relative terms, cooperation is more likely to break down. As predicted by the theory, when it breaks down, it first breaks down in the later stages. These results continue to hold in the four-step, two-firm markets. However, subjects cooperate longer in these markets than predicted by the model. Cooperation does not break down until the very last research step. One possible explanation for cooperation to be higher than the predicted level is that subjects exhibit some form of altruism or feel obligated to reciprocate the cooperative actions of their partner in the early stages of a market.

Understanding the sharing dynamics throughout the research process is important if one would like to design policy optimally. Since the 1980s, cooperative R&D initiatives have been encouraged by policy makers in both the US and Europe.[30] Knowing when firms are less likely to share is important in determining how cooperation should be encouraged. By illustrating the predictive power of Erkal and Minehart (2008), our results demonstrate, depending on market conditions, when it is necessary for policy makers to target early vs. later stage research.

The consistency of the observed behavior with the theoretical predictions also suggests that the laboratory can be used for making policy inferences in situations where theory is not tractable. One such area is the formation on joint ventures when there are more than two firms. In the laboratory, one can exogenously impose asymmetric histories and observe the welfare implications of different policies for leading and lagging firms.

In addition to analyzing the predictive power of Erkal and Minehart (2008) in the lab, this paper also provides a methodological contribution to the literature on IO experiments. The original model was developed in accordance with standard practice and done in a way to provide tractability. However, it was not optimal for direct laboratory testing.

---

[30] For example, in the US, the National Cooperative Research and Production Act (NCRPA) of 1993 provides that research and production joint ventures be subject to a 'rule of reason' analysis instead of a per se prohibition in antitrust litigation. In the EU, the Commission Regulation (EC) No 2659/2000 (the EU Regulation) provides for a block exemption from antitrust laws for RJVs, provided that they satisfy certain market share restrictions and allow all joint venture participants to access the outcomes of the research.

While one might be tempted to simply assume that the basic results will hold, this need not be the case. For example, one key difference in our modified model is the possibility of simultaneous discovery which cannot occur in continuous time. Although some of the conditions remain unchanged in our modified version of the model, some of the conditions for sharing are different. Hence, the specific sharing predictions for the parameters we employ differ between the two models.

References

[1] Amir, R. 2000. "Modelling Imperfectly Appropriable R&D via Spillovers," *International Journal of Industrial Organization*, 18, 1013-1032.

[2] Amir, R. and J. Wooders. 2000. "One-Way Spillovers, Endogenous Innovator/Imitator Roles and Research Joint Ventures," *Games and Economic Behavior*, 31, 1-25.

[3] D'Aspremont, C. and A. Jacquemin. 1988. "Cooperative and Noncooperative R&D in Duopoly with Spillovers," *American Economic Review*, 78(5), 1133-1137.

[4] Belderbos, R., M. Carree, B. Diederen, B. Lokshin, and R. Veugelers. 2004. "Heterogeneity in R&D Cooperation Strategies," *International Journal of Industrial Organization,* 22, 1237-1263.

[5] Cassiman, B. and R. Veugelers. 2002. "R&D Cooperation and Spillovers: Some Empirical Evidence from Belgium," *American Economic Review,* 92(4), 1169-1184.

[6] Charness, G. and G. Genicot. 2006. "Informal Risk-Sharing in an Infinite-Horizon Experiment," available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=510862.

[7] Choi, J.P. 1993. "Cooperative R&D with Product Market Competition," *International Journal of Industrial Organization*, 11, 553-571.

[8] De Bondt, Raymond. 1997. "Spillovers and Innovative Activities," *International Journal of Industrial Organization*, 15, 1-28.

[9] Erkal, N. and D. Minehart. 2008. "Optimal Sharing Strategies in Dynamic Games of Research and Development," University of Melbourne, Department of Economics, Research Paper #1038.

[10] Erkal, N. and D. Piccinin. 2008. "Cooperative R&D under Uncertainty with Free Entry," *International Journal of Industrial Organization*, forthcoming.

[11] Hernan, R., P. Marin, and G. Siotis. 2003. "An Empirical Evaluation of the Determinants of Research Joint Venture Formation," *Journal of Industrial Economics,* 51(1), 75-89.

[12] Hey, J. and M. Reynolds. 1991. "Experiments, Games and Economics.," in Moss, S. and J. Rae (Eds.), *Artificial Intelligence and Economic Analysis*, Edward Elgar, Aldershot, 81-115.

[13] Holt, C. and S. Laury. 2002. "Risk Aversion and Incentive Effects in Lottery Choices," *American Economic Review*, 92, 1644-1655.

[14] Isaac, R. and S. Reynolds. 1988. "Appropriability and Market Structure in a Stochastic Invention Model," *Quarterly Journal of Economics,* 103, 647-671.

[15] Isaac, R. and S. Reynolds. 1992. "Schumpeterian Competition in Experimental Markets," *Journal of Economic Behaviour and Organization,* 17, 59-100.

[16] Kaiser, U. 2002. "An Empirical Test of Models Explaining Research Expenditures and Research Cooperation: Evidence for the German Service Sector," *International Journal of Industrial Organization,* 20, 747-774.

[17] Kamien, M., E. Muller, and I. Zang. 1992. "Research Joint Ventures and R&D Cartels," *American Economic Review,* 82, 1293-1306.

[18] Leahy, D. and P. Neary. 1997. "Public Policy Towards R&D in Oligopolistic Industries," *American Economic Review*, 87, 642–662.

[19] Martin, S. 2002. "Spillovers, Appropriability, and R&D," *Journal of Economics*, 75, 1-22.

[20] Poyago-Theotoky, J. 1995. "Equilibrium and Optimal Size of a Research Joint Venture in an Oligopoly with Spillovers," *Journal of Industrial Economics,* 43, 209–226.

[21] Salant, S. and G. Shaffer. 1998. "Optimal Asymmetric Strategies in Research Joint Ventures," *International Journal of Industrial Organization*, 16, 195-208.

[22] Sbriglia, P. and J. Hey. 1994. "Experiments in Multi-Stage R&D Competition," *Empirical Economics,* 19, 291-316.

[23] Silipo, D. B. 2005. "The Evolution of Cooperation in Patent Races: Theory and Experimental Evidence," *Journal of Economics*, 85, 1-38.

[24] Suetens, S. 2005. "Cooperative and Noncooperative R&D in Experimental Duopoly Markets," *International Journal of Industrial Organization*, 23, 63–82.

[25] Suzumura, K. 1992. "Cooperative and Noncooperative R&D in an Oligopoly with Spillovers," *American Economic Review,* 82, 1307-1320.

[26] Vonortas, N. 1994. "Inter-firm Cooperation with Imperfectly Appropriable Research," *International Journal of Industrial Organization*, 12, 413-435

[27] Zizzo, D. J. 2002. "Racing with Uncertainty: A Patent Race Experiment," *International Journal of Industrial Organization*, 20, 877–902.

Appendix

A   Proof of Lemma 1

In Region A, the lowest that a firm can earn at any history and in any equilibrium is the payoff it receives by conducting two steps of research on its own and producing in the output market as a duopolist. We compute this payoff by working backwards.

At $(2,2)$, the firm produces output as a duopolist and earns $\widetilde{\pi}^D = \frac{\pi^D}{r}$. At the history $(2,1)$, the lagging firm makes

$$
\begin{aligned}
V_2\left(2,1\right) &= \alpha \frac{V_2\left(2,2\right)}{\left(1+r\right)} - c + \frac{\left(1-\alpha\right)}{\left(1+r\right)}\left[\alpha\frac{V_1\left(2,2\right)}{\left(1+r\right)} - c + \frac{\left(1-\alpha\right)}{\left(1+r\right)}\left[\alpha\frac{V_1\left(2,2\right)}{\left(1+r\right)} - c + ...\right]\right] \\
&= \sum_{i=0}^{\infty}\left[\frac{\left(1-\alpha\right)}{\left(1+r\right)}\right]^i\left(\alpha\widetilde{\pi}^D - c\right) = \frac{\left(1+r\right)\left(\alpha\widetilde{\pi}^D - c\right)}{\left(\alpha+r\right)}. \quad (1)
\end{aligned}
$$

At the history $(2,0)$, the lagging firm makes

$$
V_2\left(2,0\right) = \frac{\left(1+r\right)\left(\alpha\frac{V_2(2,1,NS)}{(1+r)} - c\right)}{\alpha + r} = \frac{\left(1+r\right)\left(\alpha\frac{\frac{(1+r)\left(\alpha\widetilde{\pi}^D - c\right)}{\alpha+r}}{(1+r)} - c\right)}{\alpha + r}. \quad (2)
$$

This payoff is strictly positive if and only if

$$
\pi^D > c\frac{r}{\alpha}\left(2 + \frac{r}{\alpha}\right),
$$

which is the inequality that defines Region A.

B   Proof of Proposition 1

In Region A, by definition, no firm ever drops out of the game. To solve for the MPE, we only need to determine whether the firms share at the two symmetric histories. To derive the equilibrium sharing conditions at $(0,0)$ and $(1,1)$, we use backwards induction. To prove the proposition, we compare the equilibrium sharing conditions at $(0,0)$ and $(1,1)$ for every MPE.

The last history is $(2,2)$. At $(2,2)$, each firm produces output and earns discounted duopoly profits of

$$V_1 (2,2) = V_2 (2,2) = \pi^D + \frac{\pi^D}{(1+r)} + \frac{\pi^D}{(1+r)^2} + ... = (1+r)\,\widetilde{\pi}^D, \tag{3}$$

where $\widetilde{\pi}^D = \frac{\pi^D}{r}$.

Working backwards, the next history is either $(2,1)$ or $(1,2)$. The lagging firm makes an investment decision at these histories. The leading firm starts to earn monopoly profits until the lagging firm enters the product market. Consider the history $(2,1)$. The follower earns (1) while the leader earns

$$
\begin{aligned}
V_1 (2,1) &= \pi^M + \alpha\frac{V_1 (2,2)}{(1+r)} + \frac{(1-\alpha)}{(1+r)}\left[\pi^M + \alpha\frac{V_1 (2,2)}{(1+r)} + \frac{(1-\alpha)}{(1+r)}\left[\pi^M + \alpha\frac{V_1 (2,2)}{(1+r)} + ...\right]\right] \\
&= \sum_{i=0}^{\infty}\left[\frac{(1-\alpha)}{(1+r)}\right]^{i}\left(\pi^M + \alpha\widetilde{\pi}^D\right) = \frac{(1+r)\left(\pi^M + \alpha\widetilde{\pi}^D\right)}{(\alpha+r)}. \tag{4}
\end{aligned}
$$

Similarly, at the history $(2,0)$, the lagging and leading firms make

$$V_1 (2,0) = \frac{(1+r)\left(\pi^M + \alpha\frac{V_1(2,1)}{(1+r)} - c\right)}{(\alpha+r)} \text{ and } V_2 (2,0) = \frac{(1+r)\left(\alpha\frac{V_2(2,1)}{(1+r)} - c\right)}{(\alpha+r)}, \tag{5}$$

where $V_1 (2,1)$ and $V_2 (2,1)$ are given by (4) and (1).

Consider the history $(1,1)$. Sharing takes place if both firms unilaterally agree to share. If both firms unilaterally agree to share, as soon as one of the firms has a success, the game reaches $(2,2)$ and each firm starts to earn

$$V_1 (2,2) = V_2 (2,2) = \pi^D + \frac{\pi^D}{(1+r)} + \frac{\pi^D}{(1+r)^2} + ... = \sum_{i=0}^{\infty}\frac{1}{(1+r)^{i}}\pi^D = (1+r)\,\widetilde{\pi}^D,$$

where $\widetilde{\pi}^D = \frac{\pi^D}{r}$. If the firms unilaterally agree not to share, each firm finishes the research process on its own.

Assuming firm 1 decides to share, firm 2 also decides to share if

$$V_2 (1,1;S) > V_2 (1,1;NS) \tag{6}$$

where

$$V_2\left(1,1;S\right) = \left(\frac{1+r}{r+2\alpha-\alpha^2}\right)\left[\alpha^2\frac{V_2\left(2,2\right)}{\left(1+r\right)} + 2\alpha\left(1-\alpha\right)\left(\frac{V_2\left(2,2\right)}{\left(1+r\right)}\right) - c\right]$$
$$= \left(\frac{1+r}{r+2\alpha-\alpha^2}\right)\left[\alpha\left(2-\alpha\right)\widetilde{\pi}^D - c\right] \qquad (7)$$

and

$$V_2\left(1,1;NS\right) = \left(\frac{1+r}{r+2\alpha-\alpha^2}\right)\left[\alpha^2\frac{V_2\left(2,2\right)}{\left(1+r\right)} + \alpha\left(1-\alpha\right)\left(\frac{V_2\left(2,1\right)+V_2\left(1,2\right)}{\left(1+r\right)}\right) - c\right].$$

Substituting for $V_2\left(2,1\right)$ and $V_2\left(1,2\right)$ (which is equal to $V_1\left(2,1\right)$) from (1) and (4) yields

$$V_2\left(1,1;NS\right) = \left(\frac{1+r}{r+2\alpha-\alpha^2}\right)\left[\alpha^2\widetilde{\pi}^D + \left(1-\alpha\right)\alpha\left(\frac{\left(\pi^M + 2\alpha\widetilde{\pi}^D - c\right)}{\alpha+r}\right) - c\right]. \qquad (8)$$

These expressions imply that the sharing condition (6) simplifies to

$$2\pi^D + c > \pi^M. \qquad (9)$$

This condition holds, strictly fails, or holds as an equality. We consider each possibility in turn.

Case 1: The sharing condition at (1,1) holds. In this case, there are two continuation equilibria at $\left(1,1\right)$. In one equilibrium, the firms agree to share and in the other one, they do not share. This is because each firm shares at $\left(1,1\right)$ if the other firm does. Assuming firm 1 does not share, firm 2 gets the same payoff whether it chooses to share or not.

Case 1a: The firms share at (1,1). Consider the sharing decision at $\left(0,0\right)$. The sharing condition is $V_2\left(0,0;S\right) > V_2\left(0,0;NS\right)$, where

$$V_2\left(0,0;S\right) = \frac{\left(2-\alpha\right)\alpha V_2\left(1,1\right) - \left(1+r\right)c}{r+2\alpha-\alpha^2} \qquad (10)$$

and

$$V_2\left(0,0;NS\right) = \left(\frac{1+r}{r+2\alpha-\alpha^2}\right)\left[\alpha^2\frac{V_2\left(1,1\right)}{\left(1+r\right)} + \alpha\left(1-\alpha\right)\left(\frac{V_2\left(0,1\right)+V_2\left(1,0\right)}{\left(1+r\right)}\right) - c\right]. \qquad (11)$$

Since the firms share at $(1,1)$, we can substitute for $V_2(1,1;S)$ from (7). Moreover, note that

$$V_2(0,1) = \left(\alpha^2 \frac{V_2(1,2)}{(1+r)} + \alpha(1-\alpha)\left(\frac{V_2(1,1)}{(1+r)} + \frac{V_2(0,2)}{(1+r)}\right) - 2c\right)\left(\frac{1+r}{r+2\alpha-\alpha^2}\right) \quad (12)$$

and

$$V_2(1,0) = \left(\alpha^2 \frac{V_2(2,1)}{(1+r)} + \alpha(1-\alpha)\left(\frac{V_2(1,1)}{(1+r)} + \frac{V_2(2,0)}{(1+r)}\right) - 2c\right)\left(\frac{1+r}{r+2\alpha-\alpha^2}\right). \quad (13)$$

We can substitute for $V_2(2,1)$, $V_2(1,2)$, $V_2(0,2)$ and $V_2(2,0)$ from (1), (4) and (5).

Simplifying the sharing condition $V_2(0,0;S) > V_2(0,0;NS)$ yields

$$2\pi^D \left(\begin{array}{c} r^2(2-\alpha) \\ +2\alpha r(3-2\alpha) \\ +\alpha^2(5-\alpha(5-\alpha)) \end{array}\right) + c\left(\begin{array}{c} r^2(3-2\alpha) \\ +2\alpha r(4-3\alpha) \\ +\alpha^2(6-\alpha(6-\alpha)) \end{array}\right) > \pi^M(r+\alpha(2-\alpha))^2. \quad (14)$$

It is straightforward to show that (14) holds whenever (9) does. Hence, for parameter values such that the sharing condition (9) holds, there is a MPE such that the firms share at both $(0,0)$ and $(1,1)$. The sharing pattern is (S,S).

Case 1b: The firms do not share at (1,1). Consider the sharing decision at $(0,0)$. Taking into account the fact that the firms do not share at $(1,1)$ and proceeding in the same way as above, the sharing condition $V_2(0,0;S) > V_2(0,0;NS)$ simplifies to

$$2\pi^D \alpha \left(\begin{array}{c} r(2+r) \\ +\alpha(3-\alpha(3-\alpha)) \end{array}\right) + c(r+(2-\alpha)\alpha)^2 > \pi^M \left(\begin{array}{c} 2r\alpha^2 + r^2(2\alpha-1) \\ +\alpha^2(2-\alpha(2-\alpha)) \end{array}\right) \quad (15)$$

It is straightforward to show that this condition holds whenever (9) does. Hence, for parameter values such that the sharing condition (9) holds, there is a MPE such that the firms share at $(0,0)$ but not at $(1,1)$. The sharing pattern is (S,NS).

Case 2. The sharing condition at (1,1) strictly fails. In this case, there are three continuation equilibria at $(1,1)$. In one equilibrium, both firms choose not to share. In the other two equilibria, one firm chooses not to share and the other firm chooses to share. This is because each firm prefers not to share at $(1,1)$ if the other firm does. Assuming firm 1 does not share, firm 2 gets the same payoff whether it chooses to share or not. Since sharing takes place if both firms agree to share, none of the equilibria involves sharing.

The sharing condition is the same as (15). It is straightforward to show that this condition may or may not hold when (9) fails. That is, this condition is easier to satisfy than (9). For parameter values such that the sharing condition (15) holds, the equilibrium sharing pattern is (S,NS). For parameter values such that the sharing condition (15) strictly fails, the equilibrium sharing pattern is (NS,NS). For parameter values such that the sharing condition (15) holds with equality, the equilibrium sharing pattern is either (S,NS) or (NS,NS).

Case 3. The sharing condition at (1,1) holds with equality. When $2\pi^D + c = \pi^M$, the firms are indifferent between sharing and not sharing at $(1,1)$. There are multiple equilibria because the firms may choose either S or NS at $(1,1)$. Regardless of their choices, the sharing condition at $(1,0)$ is given by both (14) and (15) which coincide and hold trivially. Hence, the sharing pattern is either (S,NS) or (S,S).