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The impact of spillovers on strategic R&D under uncertainty

Mingqing Xing

School of Economics and Management and Neural Decision Science Laboratory, Weifang University, Weifang, China

ABSTRACT
This study examines the impact of technological spillovers on competitive and cooperative R&D investments under uncertainty. It assumes that the innovation size is given and an increase in R&D expenditure increases the probability of success. It focuses on the symmetric equilibrium and finds that: (i) the equilibrium R&D expenditure under R&D competition (resp. R&D cooperation) may increase (resp. decrease) with the degree of spillovers if the spillovers are sufficiently small, the innovation size is big enough and the probability of success is high (resp. low) enough; (ii) under R&D competition the privately optimal R&D expenditure may overshoot the social optimum if the spillovers are sufficiently small; (iii) under R&D cooperation the private optimum is socially insufficient regardless of the size of spillovers.

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1. Introduction

As firms that devote resources to develop a new product or new technology do not determine whether they will succeed (or how much time they will spend), there exists uncertainty on the outcome of R&D activity (Silipo & Weiss, 2005). Most of the existing literature on R&D with uncertainty examines patent races, in which the invention time of technology is the variable of interest (Bloch & Markowitz, 1996; Cai, Zeng, & Xia, 2011; Dasgupta & Stiglitz, 1980; Grenadier, 2000; Harris & Vikers, 1987). Much less work has been done on strategic R&D investments with uncertainty. Marjit (1991), Combs (1992), Kabiraj (2007) and Chattopadhyay and Kabiraj (2015) examine the role of uncertainty on the incentives of firms for doing cooperative research. Tishler (2008), Zhang, Mei, and Zhong (2013) and Xing (2014) analyse firms' optimal choice of R&D risk among R&D projects with identical expected outcomes. Moreover, Matsumura (2003) and Kitahara and Matsumura (2006), respectively, investigate welfare implications and efficient subsidies for strategic R&D investments when firms engage in stochastic cost-reducing R&D.

When technology spillovers occur in an industry, successful firms cannot appropriate all of the gains from the outcome of the R&D activity. This public good aspect associated

CONTACT Mingqing Xing mqxing1979@163.com

with R&D investments may weaken firms' incentives to invest in R&D. Many studies focus on spillover effects from firms' R&D activity. d'Aspremont and Jacquemin (1988) originally presented a duopoly model to observe R&D cooperation between firms experiencing spillover effects. Their work has spawned numerous extensions (Boivin & Vencatachellum, 2002; Kamien, Muller, & Zhang, 1992; Leahy & Neary, 1997; Slivko & Theilen, 2014; Yang & Nie, 2015). However, only a few studies on R&D have considered both uncertainty and spillovers. Most of them analyse the effects of uncertainty and spillovers on firms' incentives for R&D cooperation (Amir, Evstigneev, & Wooders, 2003; Choi, 1993; Hinloopen, 2008; Silipo & Weiss, 2005).

In the deterministic model of d'Aspremont and Jacquemin (1988), equilibrium R&D expenditure under competition (resp. cooperation) certainly decreases (resp. increases) with the extent of spillovers, and private R&D expenditure is socially insufficient under both competition and cooperation R&D.[1] Although most studies assume that R&D succeeds with probability one, most R&D projects fail with a positive probability. In addition, technology spillover is very common in most industries. Therefore, it is interesting to investigate the effect of uncertainty on the relationship between spillovers and R&D investments. This paper introduces uncertainty into the model of d'Aspremont and Jacquemin (1988).[2] The objective of this study is to re-examine the impact of technological spillovers on firms' R&D incentives and the welfare implication of strategic R&D in a duopoly in the presence of uncertainty. The innovation size is given, and it is assumed that an increase in R&D expenditure increases the probability of success. The study focuses on the symmetric equilibrium and finds that, different from the results of d'Aspremont and Jacquemin (1988), the equilibrium R&D expenditure under competition (resp. cooperation) may increase (resp. decrease) as the degree of spillovers increases, and the private optimum under R&D competition may overshoot the social optimum if the spillovers are small enough.

The remainder of this study is organised as follows. Section 2 describes the basic model, and sections 3 and 4 investigate the private optimum under R&D competition and R&D cooperation, respectively. The social optimum is analysed in section 5. The final section presents conclusions.

2. The model

Consider a market populated by an infinite number of consumers and two firms which produce a homogeneous good. As in d'Aspremont and Jacquemin (1988), Hinloopen (2008) and many other papers, the inverse demand function is given by:

$$p = a - Q_1 - Q_2 \tag{1}$$

In (1), p is the price of product and Q_i is the output of firm i ($i = 1, 2$). Following d'Aspremont and Jacquemin (1988), a is assumed to satisfy $a > 0$ and $a \geq Q_1 + Q_2$.

We consider a two-stage game. In the first stage, each firm undertakes R&D activity to lower its marginal cost. Assume that the R&D output is uncertain. It is x_i ($x_i > 0$) ($i = 1, 2$) if firm i succeeds and it is 0 if firm i fails. Moreover, firm i succeeds with probability q_i ($0 \leq q_i \leq 1$). Assume that the R&D output (x_i) is exogenous and q_i is the choice variable of firm i (it can also be interpreted as the chosen research intensity) (Matsumura, 2003). R&D yields technological spillovers for the other firm by lowering its marginal production cost. Let c_i denote the marginal cost of firm i. There are four possible outcomes: (i) $c_i = c - x_i - \beta x_j$

$(i, j = 1, 2, i \neq j)$ if both firms succeed, where c $(x_i + \beta x_j < c < a)$ is the marginal cost before R&D and β $(0 \leq \beta \leq 1)$ measures the technological spillovers; (ii) $c_i = c - x_i$ and $c_j = c - \beta x_i$ if firm i succeeds and firm j fails; (iii) $c_i = c - \beta x_j$ and $c_j = c - x_j$ if firm j succeeds and firm i fails; (iv) $c_i = c_j = c$ if both firms fail. In the second stage, firms know the R&D outcome, and they behave in Cournot competition to decide how much to produce.

The profit function of firm i is given by:

$$\pi_i = (p - c_i)Q_i - I(q_i) \tag{2}$$

In (2), $I(q_i)$ is the R&D cost of firm i. Assume that $\frac{\partial I}{\partial q_i} > 0$, $\lim_{q_i \to 0} \frac{\partial I}{\partial q_i} = 0$ and $\frac{\partial^2 I}{\partial q_i^2} > 0$, and that $\frac{\partial^2 I}{\partial q_i^2}$ is big enough, which guarantees that the stability conditions for R&D are satisfied and the equilibrium and socially optimal outcome are unique and interior.

3. R&D competition

Firms compete in both the production and the R&D stages in this section. In the second stage, each firm chooses the output to maximise its operating profits. The equilibrium output of firm i is given by:

$$Q_i = \frac{a - 2c_i + c_j}{3} \tag{3}$$

The resulting profit of firm i is:

$$\pi_i = \frac{1}{9}(a - 2c_i + c_j)^2 - I(q_i) \tag{4}$$

In the first stage, firms decide their R&D expenditure. In this stage the R&D outcomes are uncertain. According to (4), the expected profit for firm i is:

$$E\pi_i = \frac{1}{9}\begin{pmatrix} q_i q_j[a - c + (2-\beta)x_i + (2\beta - 1)x_j]^2 + q_i(1 - q_j)[a - c + (2-\beta)x_i]^2 \\ +(1 - q_i)q_j[a - c + (2\beta - 1)x_j]^2 + (1 - q_i)(1 - q_j)(a - c)^2 \end{pmatrix} - I(q_i) \tag{5}$$

Note that, to ensure expected outputs are positive in all possible cases, we assume $a - c + (2\beta - 1)x_j > 0$ $(j = 1, 2)$ for $\beta \in [0, 1]$. Now each firm chooses the probability of success to maximise its expected profit. The first-order conditions yield:

$$\frac{\partial E\pi_i}{\partial q_i} = \frac{(2-\beta)x_i}{9}[2(a - c) + (2-\beta)x_i + 2q_j(2\beta - 1)x_j] - \frac{\partial I}{\partial q_i} = 0 \tag{6}$$

Thus, the following equation is obtained:

$$\frac{(2-\beta)x_i}{9}[2(a - c) + (2-\beta)x_i + 2q_j(2\beta - 1)x_j] = \frac{\partial I}{\partial q_i} \tag{7}$$

Given $x_i = x_j = x$, when $q_i = q_j = q$, we can derive:

$$\frac{(2-\beta)x}{9}[2(a - c) + (2-\beta)x + 2q(2\beta - 1)x] = \frac{\partial I}{\partial q} \tag{8}$$

Note that we only consider a symmetric equilibrium in this study. Let q^* denote the equilibrium probability of success, which is solved from Equation (8). We assume that the model parameters can ensure $0 \leq q^* \leq 1$. Zhang and Zhang (1996), Amir and Wooders (1998) and Matsumura (2003) suggest that the equilibrium predicts play well when it is stable, but predicts play poorly when it is unstable. The stability condition requires q^* meeting:

$$\frac{\partial^2 I}{\partial q^2} > \frac{2(2-\beta)|2\beta-1|x^2}{9} \tag{9}$$

The above condition can guarantee Nash equilibrium in R&D stage is unique and symmetric.

Proposition 1. (i) when β is big enough (meet $1-\beta < \frac{a-c}{3x}$), $\frac{\partial q^*}{\partial \beta} < 0$; (ii) when β is small enough, $\frac{\partial q^*}{\partial \beta} > 0$ if both x and q^* are big enough (meet $q^*(5-4\beta) > \frac{a-c}{x} + 2 - \beta$).

Proof. (i) because q^* satisfies Equation (8), we have:

$$x(2-\beta)\left[2(a-c)+(2-\beta)x+2q^*(2\beta-1)x\right] = 9\frac{\partial I(q^*)}{\partial q} \tag{10}$$

Taking the derivative of β on both sides of Equation (10) yields:

$$2x[-(a-c)-(2-\beta)x+q^*(5-4\beta)x+(2-\beta)(2\beta-1)x\frac{\partial q^*}{\partial \beta}] = 9\frac{\partial^2 I(q^*)}{\partial q^2}\frac{\partial q^*}{\partial \beta} \tag{11}$$

We obtain:

$$\frac{\partial q^*}{\partial \beta} = \frac{2x[-(a-c)-(2-\beta)x+q^*(5-4\beta)x]}{9\partial^2 I(q^*)/\partial q^2 - 2(2-\beta)(2\beta-1)x^2} \tag{12}$$

According to (9), $9\frac{\partial^2 I(q^*)}{\partial q^2} - 2(2-\beta)(2\beta-1)x^2 > 0$. Thus, $\frac{\partial q^*}{\partial \beta} < (>)\, 0$ is equivalent to $-(a-c)-(2-\beta)x+q^*(5-4\beta)x < (>) 0$. Because $0 \leq q^* \leq 1$ and $0 \leq \beta \leq 1$, we can derive $-(a-c)-(2-\beta)x+q^*(5-4\beta)x \leq -(a-c)+3(1-\beta)x < 0$ if $1-\beta < \frac{a-c}{3x}$. Thus, when β is big enough and meet $1-\beta < \frac{a-c}{3x}$, $\frac{\partial q^*}{\partial \beta} < 0$; (ii) $-(a-c)-(2-\beta)x+q^*(5-4\beta)x > 0$ is equivalent to $q^*(5-4\beta) > \frac{a-c}{x} + 2 - \beta$. Thus, when β is small enough and both x and q^* are big enough (meet $q^*(5-4\beta) > \frac{a-c}{x} + 2 - \beta$), $\frac{\partial q^*}{\partial \beta} > 0$.

When the technological spillovers are sufficiently large, the rival firm can free-ride on most of the R&D outputs and a firm cannot gain great competitive advantage if it succeeds. In this case, the incentive to improve the probability of success reduces if the degree of spillovers increases. However, the public good aspect associated with R&D is not necessarily detrimental for private investment in competitive R&D.[3] According to the second part of Proposition 1, when the spillovers are sufficiently small, an increase in the degree of spillovers may increase the level of R&D expenditure (see Figure 1).[4] This is different from the well-known result that an increase in the degree of spillovers certainly reduces the level of R&D expenditure in a competitive R&D market (d'Aspremont & Jacquemin, 1988[5]; Choi, 1993; Silipo & Weiss, 2005). The intuition behind this result is as follows. Given a and c, if a firm can obtain a high innovation size with large probability and the spillovers are small,

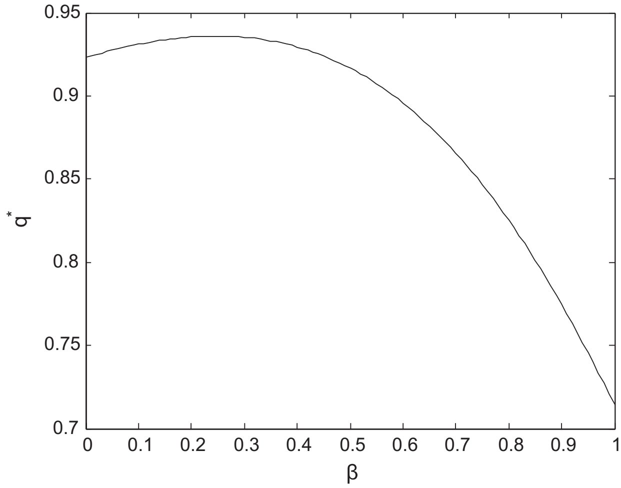

Figure 1. The impact of β on q^* (when $a = 8$, $c = 4$, $x = 2$ and $I(q_i) = 2q_i^2$ ($i = 1, 2$)). Source: Numerical simulations on the basis of the settings given in assumption.

it gains huge competitive advantage once successful. In this case, the incentive to increase the probability of success is high. Since firms do not eliminate the duplication of R&D efforts, they invest more for the same expected profit if the degree of spillovers increases.

4. R&D cooperation

In this section, firms compete in the production stage and cooperate in the R&D stage.[6] Here, firms invest in R&D separately, and coordinate their R&D expenditures so as to maximise their joint profit. The solution to the two-stage game starts by first solving equilibrium outputs in the second stage. The equilibrium output and profit of firm *i* are still given by (3) and (4), respectively. Thus, the expected joint profit equals $E\Pi = E(\pi_1 + \pi_2) = E\pi_1 + E\pi_2$, i.e.,

$$E\Pi = \sum_{\substack{i=1 \\ i \neq j}}^{2} \left\{ \frac{1}{9} \begin{pmatrix} q_i q_j [a - c + (2-\beta)x_i + (2\beta - 1)x_j]^2 + q_i(1-q_j)[a - c + (2-\beta)x_i]^2 \\ +(1-q_i)q_j[a - c + (2\beta - 1)x_j]^2 + (1-q_i)(1-q_j)(a-c)^2 \end{pmatrix} - I(q_i) \right\} \quad (13)$$

The first-order conditions yield:

$$\frac{x_i}{9}\{2(a-c)(1+\beta) + [(2-\beta)^2 + (2\beta-1)^2]x_i + 4q_j(2-\beta)(2\beta-1)x_j\} = \frac{\partial I}{\partial q_i} \quad (14)$$

Given $x_i = x_j = x$, when $q_i = q_j = q$ (i.e., we only consider a symmetric equilibrium), there is:

$$\frac{x}{9}\{2(a-c)(1+\beta) + [(2-\beta)^2 + (2\beta-1)^2 + 4q(2-\beta)(2\beta-1)]x\} = \frac{\partial I}{\partial q} \quad (15)$$

Let $q^\#$ denote the equilibrium probability, which is solved from Equation (15). We assume that the model parameters can ensure $0 \leq q^\# \leq 1$. The stability condition requires $q^\#$ meeting:

$$\frac{\partial^2 I}{\partial q^2} > \frac{4(2-\beta)|2\beta-1|x^2}{9} \quad (16)$$

Proposition 2. (i) when β is big enough (meet $\beta > \frac{4}{5} - \frac{a-c}{5x}$), $\frac{\partial q^{\#}}{\partial \beta} > 0$; (ii) when β is small enough, $\frac{\partial q^{\#}}{\partial \beta} < 0$ if x is big enough and $q^{\#}$ is small enough (meet $q^{\#}(5-4\beta) < \frac{4-5\beta}{2} - \frac{a-c}{2x}$).

Proof. (i) because $q^{\#}$ satisfies Equation (15), we have:

$$x\{2(a-c)(1+\beta) + [(2-\beta)^2 + (2\beta-1)^2 + 4q^{\#}(2-\beta)(2\beta-1)]x\} = 9\frac{\partial I(q^{\#})}{\partial q} \quad (17)$$

Taking the derivative of β on both sides of Equation (17) yields:

$$2x\{(a-c) - (4-5\beta)x + 2q^{\#}(5-4\beta)x + 2(2-\beta)(2\beta-1)x\frac{\partial q^{\#}}{\partial \beta}\} = 9\frac{\partial^2 I(q^{\#})}{\partial q^2}\frac{\partial q^{\#}}{\partial \beta} \quad (18)$$

We can derive:

$$\frac{\partial q^{\#}}{\partial \beta} = \frac{2x[(a-c) - (4-5\beta)x + 2q^{\#}(5-4\beta)x]}{9\partial^2 I(q^{\#})/\partial q^2 - 4(2-\beta)(2\beta-1)x^2} \quad (19)$$

According to (16), $9\frac{\partial^2 I(q^{\#})}{\partial q^2} - 4(2-\beta)(2\beta-1)x^2 > 0$. Thus, $\frac{\partial q^{\#}}{\partial \beta} > (<) 0$ is equivalent to $(a-c) - (4-5\beta)x + 2q^{\#}(5-4\beta)x > (<) 0$. Because $0 \le q^{\#} \le 1$ and $0 \le \beta \le 1$, we can obtain $(a-c)-(4-5\beta)x + 2q^{\#}(5-4\beta)x \ge (a-c)-(4-5\beta)x$. Moreover, $(a-c)-(4-5\beta)x > 0 \Leftrightarrow \beta > \frac{4}{5} - \frac{a-c}{5x}$. Thus, $\frac{\partial q^{\#}}{\partial \beta} > 0$ if $\beta > \frac{4}{5} - \frac{a-c}{5x}$; (ii) $(a-c) - (4-5\beta)x + 2q^{\#}(5-4\beta)x < 0 \Leftrightarrow q^{\#}(5-4\beta) < \frac{4-5\beta}{2} - \frac{a-c}{2x}$. Thus, when β and $q^{\#}$ are small enough and x is big enough (meet $q^{\#}(5-4\beta) < \frac{4-5\beta}{2} - \frac{a-c}{2x}$), $\frac{\partial q^{\#}}{\partial \beta} < 0$.

The first part of Proposition 2 demonstrates that under R&D cooperation the technological spillovers can promote R&D expenditures in the presence of sufficiently large spillovers. The reason for this result is as follows. Under the current regime, firms agree to coordinate R&D activity to maximise the sum of overall expected profits, so the technological spillovers are partly internalised (Kamien et al., 1992). R&D investment by one firm can generate two externalities on the other firm (Hinloopen, 1997; Yi, 1996). On the one hand, if the firm which invests in R&D succeeds, it increases its production efficiency and steals business from the other firm by becoming more efficient in production (identified as the business-stealing externality). On the other hand, the rival firm gets some of the benefits of R&D due to the spillovers, and thereby its production efficiency also increases (identified as the free-riding externality). Obviously, the business-stealing externality is negative and the free-riding externality is positive. When the spillovers are sufficiently large, a firm can free-ride on most of its competitor's R&D outputs. The positive free-riding externality dominates the negative business-stealing externality so that an increase in a firm's R&D spending raises the other firm's expected profit (further raises the expected joint profit). In this case, the technological spillovers can increase firms' R&D expenditure under cooperative R&D.

According to the second part of Proposition 2, when the spillovers are sufficiently small, an increase in the size of spillovers may decrease the level of R&D expenditure under cooperation (see Figure 2).[7] This is different from the well-known result that an increase in the degree of spillovers certainly increases the level of R&D expenditure under cooperation (d'Aspremont & Jacquemin, 1988).[8] The intuition behind this result is as follows. When the spillovers are small enough, the negative business-stealing externality dominates the positive

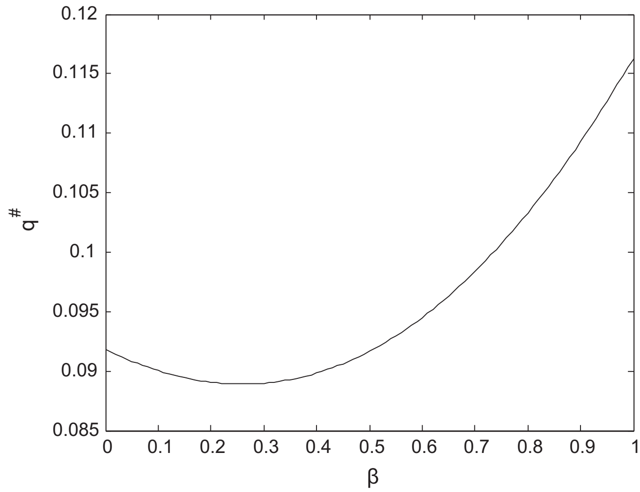

Figure 2. The impact of β on $q^{\#}$ (when $a = 6$, $c = 4$, $x = 1$ and $I(q_i) = 5q_i^2$ ($i = 1, 2$)). Source: Numerical simulations on the basis of the settings given in assumption.

free-riding externality so that an increase in a firm's R&D spending lowers the other firm's expected profit. If a firm engages in a project with high innovation size and high risk, the increase of its expected profit is lower than the reduction of the other firm's expected profit (therefore the expected joint profit decreases) as its R&D expenditure increases. In this case, the technological spillovers can decrease firms' R&D expenditure under cooperative R&D.

5. The social optimum

Social welfare, defined as the sum of the firms' profit and the consumers' surplus, is written by:

$$sw = \pi_1 + \pi_2 + cs \tag{20}$$

In (20), cs represents the consumer surplus.

Assume that the social planner adjusts the R&D investment and the product outputs are determined by competition. According to (3), (4) and (20), the social welfare is:

$$sw = \frac{1}{6}\{[a-c+(2-\beta)x_1+(2\beta-1)x_2]^2+[a-c+(2-\beta)x_2+(2\beta-1)x_1]^2\} - I(q_1) - I(q_2) \tag{21}$$

Since the R&D outcomes are uncertain, the social welfare is an expectation value. The expected social welfare is given by:

$$Esw = \frac{1}{6}\left(\begin{array}{l} q_1q_2\{[a-c+(2-\beta)x_1+(2\beta-1)x_2]^2+[a-c+(2-\beta)x_2+(2\beta-1)x_1]^2\} \\ +q_1(1-q_2)\{[a-c+(2-\beta)x_1]^2+[a-c+(2\beta-1)x_1]^2\}+(1-q_1)q_2\{[a-c \\ +(2\beta-1)x_2]^2+[a-c+(2-\beta)x_2]^2\}+(1-q_1)(1-q_2)[(a-c)^2+(a-c)^2] \end{array}\right) - I(q_1) - I(q_2) \tag{22}$$

The first-order conditions yield:

$$\frac{x_i}{6}\{2(a-c)(1+\beta)+[(2-\beta)^2+(2\beta-1)^2]x_i+4q_j(2-\beta)(2\beta-1)x_j\} = \frac{\partial I}{\partial q_i} \tag{23}$$

Given $x_i = x_j = x$, when $q_i = q_j = q$, we obtain:

$$\frac{x}{6}\{2(a-c)(1+\beta)+[(2-\beta)^2+(2\beta-1)^2+4q(2-\beta)(2\beta-1)]x\}=\frac{\partial I}{\partial q} \tag{24}$$

Let q^s denote the socially optimal probability, which is solved from Equation (24). We assume that the model parameters can ensure $0 \le q^s \le 1$. The stability condition requires q^s meeting:

$$\frac{\partial^2 I}{\partial q^2} > \frac{2(2-\beta)|2\beta-1|x^2}{3} \tag{25}$$

We set $\bar{q} = \frac{(2-\beta)^2+3(2\beta-1)^2-2(1-5\beta)(a-c)/x}{8(2-\beta)(1-2\beta)}$ and $\bar{x} = \frac{2(1-5\beta)(a-c)}{(2-\beta)^2+3(2\beta-1)^2}$, and then can prove the following results.

Proposition 3. (i) when β is big enough (meet $\beta \ge \frac{1}{2}$), $q^* < q^s$; (ii) when β is small enough (meet $\beta < \frac{1}{5}$), $q^* > q^s$ if $x < \bar{x}$, $q^* < q^s$ if $x > \bar{x}$ and $q^* < \bar{q}$, and $q^* > q^s$ if $x > \bar{x}$ and $q^* > \bar{q}$.

Proof. (i) q^* and q^s satisfy (8) and (24) respectively. By seeking the difference between the left-hand side of (24) and (8), we have:

$$\Delta = \frac{x^2}{18}[(2-\beta)^2+3(2\beta-1)^2-2(1-5\beta)\frac{a-c}{x}+8q(2-\beta)(2\beta-1)] \tag{26}$$

Obviously, when $\beta \ge \frac{1}{2}$, $\Delta > 0$. From the convexity of $I(q)$, we get the first part of Proposition 3; (ii) when $\beta < \frac{1}{5}$, $(2-\beta)^2+3(2\beta-1)^2-2(1-5\beta)\frac{a-c}{x} < (>)\, 0 \Leftrightarrow x < (>)\, \bar{x}$. Thus, when $\beta < \frac{1}{5}$ and $x < \bar{x}$, $\Delta < 0$. Moreover, when $\beta < \frac{1}{5}$, we can prove that $\Delta > 0$ if $x > \bar{x}$ and $q < \bar{q}$, and $\Delta < 0$ if $x > \bar{x}$ and $q > \bar{q}$. From the convexity of $I(q)$, we derive the second part of Proposition 3.

This proposition implies that, from a social-welfare perspective, when the technological spillovers are sufficiently large, the R&D levels for individual firms are too low under competition in R&D. However, when the spillovers are sufficiently small, they are too high if both the innovation size and the probability of success are high enough (or if the innovation size is low enough), and they are still too low if the innovation size is high enough but the probability of success is low enough. This is different from the study of d'Aspremont and Jacquemin (1988), where the private optimum under R&D competition is insufficient for all sizes of spillovers. The logic behind this proposition is as follows. When a firm decides on its R&D expenditure under competition, it does not care about the positive externalities of R&D on its competitor's expected profit and the expected consumer surplus. However, the social planner takes into account both the firms' expected profit and the expected consumer surplus and therefore maximises the sum of the two. Given q_2 (q_1), regardless of the spillover size, the expected industrial product output (resp. the expected price) is more (resp. lower) if firm 1 (firm 2) succeeds than if it fails. Thus, the expected consumer surplus increases if firm 1 (firm 2) invests more to increase the probability of success. When the spillovers are sufficiently large, firm 2 (firm 1) can free-ride on most of the R&D outputs if firm 1 (firm 2) succeeds. Thus, given q_2 (q_1), if firm 1 (firm 2) increases R&D expenditure, the expected profit of firm 2 (firm 1) increases. Thus, firms do not invest in R&D with enough high probability of success for the social optimum. When the spillovers are sufficiently small, firm 2 (firm 1) can free-ride on a few of the R&D outputs if firm 1 (firm 2) succeeds. Given q_2 (q_1), firm 2's (firm 1's) expected profit decreases if firm 1 (firm 2) increases R&D expenditure. Moreover, the expected consumer surplus increases if firm 1 (firm 2) invests more to increase the probability of success. However, the decrease of the expected profit of firm 2 (firm 1) exceeds the increase of the expected consumer surplus if the innovation size is small enough (or if firm 1 (firm 2) gets a big R&D output with enough high probability), and it is lower than the increase of the expected consumer surplus if firm 1 (firm 2) obtains a big R&D output with enough low probability. Thus, if the innovation size is small enough or firm 1 (firm 2) gets a big R&D output with enough high probability (resp. if firm 1 (firm 2) gets a big R&D output with enough low probability), firms invest in R&D with too high (resp. too low) probability of success for the social optimum.

These results imply that the optimal tax subsidy for investment under R&D competition crucially depends on the degree of spillovers, the innovation size and the probability of success. For examples, if firms engage in projects which are relatively easy to result in a success with high innovation size, subsidies on firms' R&D expenditure improve welfare when the degree of spillovers is large enough, but they are harmful when the degree of spillovers is small enough.

It is generally agreed that, in the automobile industry, the spillovers of foundational research and applied foundational research are much higher than those of applied research. In China, the government is implementing an innovation-driven development strategy, and mainly funds automobile firms engaging in foundational research and applied foundational research, or firms engaging in applied research with big innovation size and high risk. However, it generally does not fund automobile firms who only engage in applied research with small innovation size. According to Proposition 3, this policy can increase social welfare.

Proposition 4. $q^{\#} < q^{s}$.

Proof. $q^{\#}$ and q^{s} satisfy (15) and (24) respectively. By seeking the difference between the left-hand side of (24) and (15), we have:

$$\Delta = \frac{x}{18}\{2(a-c)(1+\beta) + [(2-\beta)^2 + (2\beta-1)^2 + 4q(2-\beta)(2\beta-1)]x\} > 0 \quad (28)$$

From the convexity of $I(q)$, we obtain Proposition 4.

This proposition implies that, regardless of the degree of spillovers, the R&D levels for individual firms are too low under cooperation in R&D from a social-welfare perspective. In other words, firms have an insufficient incentive for increasing the probability of success if they cooperate in R&D. The intuition behind this result is as follows. Given q_2 (q_1), the expected industrial product output (resp. the expected price) is more (resp. lower) if firm 1 (firm 2) succeeds than if it fails regardless of the spillover size. Consequently, the expected consumer surplus increases if firm 1 (firm 2) increases R&D expenditure. When firms decide on the R&D expenditure under cooperation, they only care about the expected joint profits and do not take into account the expected consumer surplus. However, the social planner considers both the firms' expected profits and the expected consumer surplus and therefore maximises the sum of the two. Thus, firms do not invest in R&D with enough high probability of success for the social optimum.

This result implies that, regardless the degree of spillovers and the project's innovation size and risk, subsidies on firms' R&D expenditure improve welfare under cooperative R&D. In China, there is not much R&D cooperation among competitive firms in most high-tech industries. The government encourages high-tech firms doing more R&D cooperative activities, and generally gives them a certain amount of subsidy. According to Proposition 4, such a policy will contribute to social welfare.

6. Conclusions

In this paper we investigate the impact of technological spillovers on non-cooperative or cooperative R&D investments by introducing uncertainty. In the models, an increase in R&D expenditure increases the probability of success. We find that, under certain conditions, the spillovers increase (resp. reduce) the equilibrium R&D expenditure under non-cooperative R&D (resp. cooperative R&D). This is different from the well-known results in the deterministic model (d'Aspremont & Jacquemin, 1988). In addition, under R&D competition the private optimum may exceed the social optimum when the spillovers are sufficiently small, and under R&D cooperation it is lower than the social optimum no matter the size of spillovers.

Notes

1. It is worth noting that there are some cases in reality that do not match these theoretical results. For example, in the smartphone industry, there exists fierce R&D competition between Apple and Huawei. On the one hand, the technology spillovers are increasing in the smartphone industry because of more frequent technical exchanges and employee turnover between firms, or/and other factors. On the other hand, Apple and Huawei continue to increase investments in smartphone R&D. This is clearly contrary to the theoretical result 'the R&D expenditure under competition certainly decreases with the extent of spillovers'. We note that the smartphone R&D has high uncertainty. However, the model of d'Aspremont and Jacquemin (1988) does not consider the uncertainty in R&D. Thus, it may be the R&D uncertainty that leads to the deviation of theory and reality.
2. The models of Matsumura (2003) also consider strategic R&D under uncertainty; however, his models ignore the spillover effects of R&D and do not consider the case of R&D cooperation.
3. It is usually considered that the technology spillovers will weaken private investment in competitive R&D. However, existing empirical literature shows that in many cases the spillovers increase R&D expenditures (Bernstein & Nadiri, 1988; Jaffe, 1988; Levin, 1988).
4. Several recent studies also emphasise the spillover may increase innovation expenditures (Chen, Nie, & Wang, 2015; Chen, Wen, & Luo, 2016). Chen et al. (2016) consider a duopoly food market where only one of the firms engages in corporate social responsibility (CSR) with negative spillover effects on its competitor, and find that CSR spillovers increase CSR firm's expenditures. In their study the CSR spillovers are negative, but we only consider the positive R&D spillovers in this paper. Chen et al. (2015) examine asymmetric competition with innovation spillover and input constraints, and find an inverted U relationship between spillover and investment difference. Different from their study, this paper emphasises the inverse-U shape between spillover and firms' innovation expenditure (see Figure 1).
5. In the model of d'Aspremont and Jacquemin (1988), the unique equilibrium solution under R&D competition is $x_i^* = \frac{(a-A)(2-\beta)}{4.5b\gamma-(2-\beta)(1+\beta)}$, $i = 1, 2$, where β is the technology spillovers parameter. We can prove $\frac{\partial x_i^*}{\partial \beta} = -\frac{(a-A)[4.5b\gamma-(2-\beta)^2]}{[4.5b\gamma-(2-\beta)(1+\beta)]^2} < 0$. Thus, the R&D level under competition decreases with the degree of spillovers for all $\beta \in [0, 1]$. Proposition 1 of this paper implies that this result may be no longer valid by considering R&D uncertainty.
6. In many countries, governments directly intervene or even prohibit the collusion of firms in the production stage (or sale stage), but they support cooperation in R&D (e.g., the National Cooperative Research Act of the United States in 1984). Thus, different from the study of d'Aspremont and Jacquemin (1988), this paper does not consider the case that firms cooperate in both production and R&D stages.

7. The empirical literature has shown that in some cases the technology spillovers may weaken firms' R&D expenditures under cooperation (Zhang, Yuan, & Xu, 2012; Zheng & Dang, 2008).
8. In the model of d'Aspremont and Jacquemin (1988), the unique equilibrium solution under R&D cooperation (firms only cooperate in R&D stage) is $x_i^* = \frac{(a-A)(\beta+1)}{4.5b\gamma-(\beta+1)^2}$, $i = 1, 2$. We can prove $\frac{\partial x_i^*}{\partial \beta} = \frac{(a-A)[4.5b\gamma+(\beta+1)^2]}{[4.5b\gamma-(\beta+1)^2]^2} > 0$. Thus, the R&D level under cooperation increases with the degree of spillovers for all $\beta \in [0, 1]$. Proposition 2 of this paper implies that this result may be no longer valid by introducing R&D uncertainty.

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