Duopoly Firms' Decisions on Disclosing Their R&D Investment Information

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Abstract

We study a quantity-setting duopoly and a price-setting duopoly in which each firm has the option of disclosing or not its cost-reducing R&D investment. Each firm's R&D outcome (or, its new marginal cost) is deterministically determined, and thus, when making its R&D investment, each firm is certain about its R&D outcome. We formally consider the following game. In the first stage, each firm decides and announces whether it will disclose its R&D investment. Next, each firm chooses – and discloses if it announced to do so – its R&D investment. Finally, the firms choose their output levels [prices] simultaneously and independently. When choosing its output level [price], each firm knows the other firm's new marginal cost only if the other firm disclosed its R&D investment. We show in both models that each firm discloses its R&D investment.

Keywords: Decision on disclosing an R&D investment; Cost-reducing R&D investment; Deterministic R&D process; Disclosure of R&D investments; Information sharing

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1. Introduction

Compulsory disclosure requirements regarding information on firms' research and development (R&D) investments are observed in some countries, such as the United States and the United Kingdom. However, in many countries including France, Germany, and Italy, there are no disclosure requirements regarding firms' R&D investments (see Hall and Oriani, 2006). Furthermore, even under compulsory disclosure requirements, firms fail to provide information on their R&D investments (see Koh and Reeb, 2015). All these imply that firms have substantial discretion on whether or not to disclose information on their R&D investments.

A natural, interesting question that arises is, then, whether firms have an incentive to disclose – and thus they actually disclose – information on their R&D investments. However, to the best of our knowledge, this question has not been addressed previously.

Accordingly, we address the question in two duopoly models in which firms have the option of disclosing or not their R&D investments. One is a quantity-setting duopoly with homogeneous products, and the other is a price-setting duopoly with differentiated products. In these duopoly models, the firms make R&D investments to reduce their production costs, and produce their products at the resulting reduced costs. Each firm's R&D outcome or, precisely, its new production cost is deterministically determined. This means that, when making its R&D investment, each firm is certain about its R&D outcome.[1]

Formally, we consider the following game. In the first stage, each firm decides and announces whether it will disclose its cost-reducing R&D investment to the public. Next, each firm chooses – and discloses if it announced to do so – its R&D investment. Finally, the firms choose their output levels [prices] simultaneously and independently. When choosing its output level [price], each firm knows the other firm's R&D outcome only if the other firm disclosed its R&D investment.

To solve the game, we first look at the subgames starting after the firms announce publicly whether they will disclose their R&D investments to the public, and then look at the firms' decisions, in the first stage, on whether or not to disclose their R&D investments.

As the main result of this paper, we show both in the quantity-setting duopoly and the price-setting duopoly that, in equilibrium, each firm announces in the first stage that it will disclose its R&D investment. A detailed explanation for this result will be given later in Section 3, but here it is in order to give a brief explanation for it. Given that the other firm announces to disclose its R&D investment, if a firm announces to withhold its R&D investment, then under our assumption that the firm (or the receiving firm) chooses its R&D investment after observing the disclosing firm's R&D investment, the disclosing firm will exercise strategic leadership in choosing an R&D investment. As a result of this, the receiving firm's new marginal cost is greater than the disclosing firm's new marginal cost, which creates a disadvantage for the receiving firm in competing in the market. By contrast, given that the other firm announces to disclose its R&D investment, if a firm also announces to disclose its R&D investment, then the firm will compete against the other firm in symmetric environments in the subsequent stages. Therefore, each firm announces to disclose its R&D investment, given its belief that the other firm announces to disclose its R&D investment.

The remainder of this paper proceeds as follows. In Section 2, we develop the quantity-setting duopoly model. Section 3 analyzes the quantity-setting duopoly, and shows that, in equilibrium, each firm discloses its R&D investment. Section 4 develops the price-setting duopoly model. In Section 5, we analyze the price-setting duopoly, and show that, in equilibrium, each firm discloses its R&D investment. Finally, Section 6 offers our conclusions.

1.1. Related literature

Cost-reducing R&D has been studied by many economists in different contexts: Haaland and Kind (2008), Tishler and Milstein (2009), Bourreau and Dogan (2010), Ishida et al. (2011), Lin and Zhou (2013), Milliou and Pavlou (2013), Tesoriere (2015), Sengupta (2016), and Baik and Kim (2020), to name a few.

In particular, Ishida et al. (2011) study a quantity-setting oligopoly in which the firms first choose their cost-reducing R&D investments, and then choose their output levels. They assume that the firms know their rivals' R&D investments and new marginal costs when they choose their output levels. Milliou and Pavlou (2013) study a vertically related industry with two upstream firms and two downstream firms. They assume that the firms' R&D investments are observable.

Tesoriere (2015) studies a quantity-setting oligopoly in which the firms in R&D cartels first choose their cost-reducing R&D investments, and then choose their output levels. He assumes that each firm knows the other firms' R&D investments and new marginal costs when the firms choose their output levels. Sengupta (2016) studies a price-setting duopoly with homogeneous products in which the firms first choose their cost-reducing R&D investments, and then choose their prices. She develops and analyzes two models: the model with observable R&D investments and the model with unobservable R&D investments.

Baik and Kim (2020) study a quantity-setting duopoly in which the firms first make their cost-reducing R&D investments, and then compete in quantities. Each firm's new marginal cost is probabilistically determined by its R&D investment before choosing its output level, but its new marginal cost is hidden from the rival firm. Note that the current paper may be viewed as extending Baik and Kim (2020) by incorporating the firms' decisions on disclosing their R&D investments.

Baik and Kim (2020) develop and analyze the observable-investments model and the unobservable-investments model. The first model assumes that each firm's R&D investment is observable to the rival firm, whereas the second model assumes that each firm's R&D investment is hidden from the rival firm. They show that the firms' equilibrium R&D investments are greater in the observable-investments model than in the unobservable-investments model. They show also that, in equilibrium, the firms' expected profits, the expected consumer surplus, and the expected social welfare are less in the observable-investments model than in the unobservable-investments model.

This paper is related to the literature on information sharing, which focuses on examining whether firms have incentives to share their private information with their rivals. For example, Vives (1984) studies duopoly models, Cournot and Bertrand, in which each firm has private information about the vertical intercept of its inverse linear demand function. He shows that, if the goods are substitutes, then no information sharing is a dominant strategy for each firm in Cournot competition, and information sharing is a dominant strategy for each firm in Bertrand competition. He shows also that, if the goods are complements, then information sharing is a dominant strategy with Cournot competition, and no information sharing is a dominant strategy with Bertrand competition.

Gal-Or (1986) studies information sharing in duopoly models in which the firms have private information about their unknown production costs. She shows that information sharing is a dominant strategy with Cournot competition and no information sharing is a dominant strategy with Bertrand competition. Theilen (2007) studies information sharing in a Cournot duopoly in which ownership and management are separated and the firms have private information on their production costs. He shows that information sharing is not always a dominant strategy.

Gill (2008) analyzes the incentives of a leading firm in a patent contest to disclose its intermediate R&D results to try to induce a lagging rival to exit the contest. He shows that, despite risk from knowledge spillovers, the leading innovator may disclose its intermediate R&D results to signal its commitment to the project. Jansen (2010) studies information sharing in an innovation contest in which the firms have private information on their R&D costs. He shows that full disclosure emerges in the case of extreme revenue spillovers, but either partial disclosure or full concealment emerges in the case of intermediate spillovers. Kovenock et al. (2015) study information sharing in contests between two firms in which each firm receives a private signal about its value of winning. They show that, when decisions on information sharing are made independently, information sharing does not occur in equilibrium whether the firms have independent values of winning or common values of winning.

2. Quantity-setting duopoly with R&D competition

Consider a quantity-setting duopoly with homogeneous products in which two profit-maximizing firms, 1 and 2, make R&D investments to reduce their production costs. Each firm first announces publicly whether it will disclose the amount of its R&D investment to the public. Then, each firm makes an R&D investment to reduce its marginal cost of production, and discloses the R&D amount if the firm announced to do so. Finally, the firms produce their products at the resulting reduced costs, and compete in quantities.

The R&D cost function of firm i, for $i = 1, 2$, is given by $K(x_i) = \gamma x_i^2/2$, where $\gamma \geq 1$, $x_i > 0$, and x_i denotes the R&D investment that firm i makes.[2] Given its constant marginal cost of c_i, the cost function of firm i is given by $V_i(q_i) = c_i q_i$ for all $q_i \in R_+$, where q_i denotes firm i's output level.

Before undertaking their R&D investments, firm i, for $i = 1, 2$, has a marginal cost c_i^M of production, which is publicly known. We assume without loss of generality that $c_1^M \leq c_2^M$.[3] When undertaking its R&D investment, each firm knows for sure how much marginal cost it can reduce by undertaking the R&D investment – that is, it is certain about its new marginal cost resulting from the R&D investment.[4] Let c_i denote firm i's new marginal cost which is deterministically determined by its R&D investment x_i. We assume that $c_i = c_i^M - \delta x_i$, where $0 < \delta < 0.75$. We assume also that c_i^M/δ is sufficiently large that $(c_i^M - \delta x_i) > 0$ in a relevant range of firm i's R&D investments.

When the firms choose their output levels, each firm knows its own new marginal cost, but cannot directly observe the other firm's new marginal cost. Specifically, each firm knows the other firm's new marginal cost only if the other firm disclosed its R&D investment. However, in the case where the other firm did not disclose its R&D investment, each firm "knows" the other firm's new marginal cost under its belief about the other firm's R&D investment.

The single market price P is determined by

$$P = \begin{cases} a - Q & \text{for } 0 \leq Q \leq a \\ 0 & \text{for } Q > a, \end{cases}$$

where a is a positive constant and $Q = q_1 + q_2$. We assume that $0 < c_1^M \leq c_2^M < a$.

We formally consider the following game. In the first stage, each firm decides independently whether it will disclose its R&D investment to the public. The firms simultaneously announce and commit to their decisions before making their R&D investments. Next, each firm independently makes a cost-reducing R&D investment – that is, firm i, for $i = 1, 2$, chooses the value of x_i – and discloses the R&D investment if the firm announced to do so. Finally, the firms choose their output levels simultaneously and independently. (We will be more specific about the game in Section 3 – in particular, about the timing of the firms' R&D investment decisions and about each firm's information on the other firm's new marginal cost.)

Let $\pi_i(c_i)$ denote firm i's gross profits of producing q_i – at the time when the firms choose their output levels – given its new marginal cost of c_i. Note that $\pi_i(c_i)$ is firm i's profits without subtracting its cost of R&D investment. Then the gross profit function for firm i is

$$\pi_i(c_i) \ = \ (a - q_i - q_j - c_i)q_i \tag{1}$$

for $i, j = 1, 2$ with $i \neq j$, where q_j denotes firm i's belief about firm j's output level.

Let $\Pi_i(x_i)$ denote firm i's profits from choosing an R&D investment of x_i – computed at the time when it chooses its R&D investment – given its output level q_i and its belief that firm j will produce q_j. Then the profit function for firm i is

$$\Pi_i(x_i) \ = \ \pi_i(c_i^M - \delta x_i) \ - \ \gamma x_i^2/2, \tag{2}$$

where $\pi_i(c_i^M - \delta x_i)$ denotes the gross profits for firm i at its new marginal cost of $(c_i^M - \delta x_i)$ which results from its R&D investment x_i.

We end this section by assuming that all of the above is common knowledge between the firms.

3. Disclosure of R&D investments

We solve the game by working *backward*: We first look at the subgames starting after the firms announce publicly whether they will disclose their R&D investments to the public, and then look at the firms' decisions, in the first stage, on whether or not to disclose their R&D investments.

There are four subgames starting after the firms announce whether they will disclose their R&D investments: the (D, D) subgame, the (D, ND) subgame, the (ND, D) subgame, and the (ND, ND) subgame, where D denotes the action of announcing that the firm will disclose its R&D investment, and ND denotes the action of announcing that the firm will not disclose its R&D investment. For example, if firm 1 announces that it will disclose its R&D investment and firm 2 announces the opposite, then the (D, ND) subgame arises.

3.1. The (D, D) *subgame*

This subgame consists of two stages. First, each firm chooses its R&D investment independently, and then the firms simultaneously disclose their R&D investments to the public. Accordingly, at the end of this stage, each firm knows the other firm's new marginal cost as well as its own new marginal cost. Next, the firms choose their output levels simultaneously and independently.

To obtain a subgame-perfect equilibrium *outcome* of the (D, D) subgame, we work backward. Consider first the stage, or the (x_1, x_2) subgame, in which the firms choose their output levels, each knowing the R&D investments, x_1 and x_2, and thus the new marginal costs, $(c_1^M - \delta x_1)$ and $(c_2^M - \delta x_2)$. Firm i seeks to maximize its gross profits $\pi_i(c_i^M - \delta x_i)$ in (1) over its output level q_i, taking the output level q_j of firm j as given, for $i, j = 1, 2$ with $i \neq j$. From the first-order condition for maximizing $\pi_i(c_i^M - \delta x_i)$, we obtain firm i's reaction function:

$$q_i(x_i, q_j) \;=\; \{a - (c_i^M - \delta x_i)\}/2 \;-\; q_j/2. \tag{3}$$

It is straightforward to check that the second-order condition for maximizing $\pi_i(c_i^M - \delta x_i)$ is satisfied.[5]

Using those reaction functions in (3), we obtain the Nash equilibrium of the (x_1, x_2) subgame:

$$q_i(x_1, x_2) \;=\; \{a - 2(c_i^M - \delta x_i) + (c_j^M - \delta x_j)\}/3 \tag{4}$$

for i, $j = 1$, 2 with $i \neq j$. Let $\pi_i(x_1,\, x_2)$, for $i = 1$, 2, denote firm i's gross profits at the Nash equilibrium of the (x_1, x_2) subgame. Then, substituting the equilibrium output levels in (4) into $\pi_i(c_i^M - \delta x_i)$ in (1), we obtain

$$\pi_i(x_1, x_2) \;=\; \{a - 2(c_i^M - \delta x_i) + (c_j^M - \delta x_j)\}^2/9. \tag{5}$$

Next, consider the stage in which firms 1 and 2 choose their R&D investments, x_1 and x_2, respectively. In this stage, each firm has perfect foresight about both $\pi_1(x_1, x_2)$ and $\pi_2(x_1, x_2)$ in (5) for any values of x_1 and x_2. Given its belief about the other firm's R&D investment, firm i, for $i = 1$, 2, seeks to maximize its profits, $\Pi_i(x_1, x_2)$, over its R&D investment x_i:

$$\Pi_i(x_1, x_2) \;=\; \pi_i(x_1, x_2) \;-\; \gamma x_i^2/2. \tag{6}$$

From the first-order condition for maximizing (6), we obtain firm i's reaction function:

$$x_i(x_j) \;=\; 4\delta(a - 2c_i^M + c_j^M - \delta x_j)/(9\gamma - 8\delta^2)$$

for $i, j = 1$, 2 with $i \neq j$. Using these two reaction functions, we obtain firm i's R&D investment, x_i^D, which is specified in the subgame-perfect equilibrium of the (D, D) subgame:

$$x_i^D \;=\; 4\delta\{3a(3\gamma - 4\delta^2) - 3c_i^M(6\gamma - 4\delta^2) + 9c_j^M\gamma\}/\{(9\gamma - 8\delta^2)^2 - 16\delta^4\}.$$

Now, substituting the firms' equilibrium R&D investments, x_1^D and x_2^D, into $q_1(x_1, x_2)$ and $q_2(x_1,\, x_2)$ in (4), we obtain the firms' equilibrium output levels, q_1^D and q_2^D, respectively. Next, substituting x_1^D and x_2^D into $\Pi_1(x_1, x_2)$ and $\Pi_2(x_1, x_2)$ in (6), we obtain the firms' equilibrium profits, Π_1^D and Π_2^D, in the (*D*, *D*) subgame.

Lemma 1 summarizes the outcomes of the (*D*, *D*) subgame.

Lemma 1. (*a*) *In the equilibrium of the* (*D*, *D*) *subgame*, *firm i chooses* $x_i^D = 4\delta\{3(3\gamma - 4\delta^2)a - 3(6\gamma - 4\delta^2)c_i^M + 9\gamma c_j^M\}/\{(9\gamma - 8\delta^2)^2 - 16\delta^4\}$ *and* $q_i^D = 3\gamma\{3(3\gamma - 4\delta^2)a - 3(6\gamma - 4\delta^2)c_i^M + 9\gamma c_j^M\}/\{(9\gamma - 8\delta^2)^2 - 16\delta^4\}$, *for* $i, j = 1, 2$ *with* $i \neq j$.
(*b*) *Firm i's equilibrium profits are* $\Pi_i^D = \gamma(9\gamma - 8\delta^2)\{3(3\gamma - 4\delta^2)a - 3(6\gamma - 4\delta^2)c_i^M + 9\gamma c_j^M\}^2/\{(9\gamma - 8\delta^2)^2 - 16\delta^4\}^2$, *for* $i, j = 1, 2$ *with* $i \neq j$.

We assume that $(9\gamma c_1^M - 4\delta^2 a) > 0$ and $(3\gamma - 4\delta^2)c_1^M(9c_1^M\gamma - 4a\delta^2) > 12\delta^2\gamma(c_2^M - c_1^M)$, which leads to $(c_i^M - \delta x_i^D) > 0$ for $i = 1, 2$. We assume also that $(3\gamma - 4\delta^2) > 3\gamma(c_2^M - c_1^M)/(a - c_2^M)$, which leads to both $x_i^D > 0$ and $q_i^D > 0$, for $i = 1, 2$. Note that, if $c_1^M = c_2^M$, then for all these we only need to assume that $(9\gamma c_1^M - 4\delta^2 a) > 0$.

It is straightforward to see that Π_i^D in part (*b*), for $i = 1, 2$, is positive under the assumptions on the parameters given in Section 2.

3.2. The (*D*, *ND*) *subgame and the* (*ND*, *D*) *subgame*

Consider a subgame in which firm *i* discloses its R&D investment to the public, but firm *j* does not, for $i, j = 1, 2$ with $i \neq j$. Note that the (*D*, *ND*) subgame arises if $i = 1$, and the (*ND*, *D*) subgame arises if $i = 2$.

We assume that firm *j* chooses its R&D investment after observing firm *i*'s R&D investment.[6] This subgame is then described as follows. First, firm *i* chooses and discloses its R&D investment. Next, after observing firm *i*'s R&D investment, firm *j* chooses its R&D investment, but does not disclose it. Finally, both firms choose their output levels simultaneously and independently. Note that, at this stage, firm *i* knows only its own new marginal cost, but firm *j* knows the new marginal costs of both firms.

We solve the subgame by viewing it as the following two-stage game.[7] In the first stage, firm i chooses its R&D investment x_i, and discloses it to the public. In the second stage, knowing the value of x_i and thus knowing its new marginal cost, firm i chooses its output level without observing firm j's R&D investment or its output level; firm j chooses its R&D investment, and then (knowing both firms' new marginal costs) chooses its output level without observing firm i's output level.

To solve this two-stage game, we work backward. In the second stage, knowing the value of x_i, firm i seeks to maximize its gross profits $\pi_i(c_i^M - \delta x_i)$ in (1) over its output level q_i, given its belief q_j about firm j's output level. From the first-order condition for maximizing $\pi_i(c_i^M - \delta x_i)$, we obtain firm i's reaction function:

$$q_i(x_i, q_j) \;=\; \{a - (c_i^M - \delta x_i)\}/2 \;-\; q_j/2. \tag{7}$$

Next, we obtain firm j's two reaction functions in the second stage. First consider firm j's decision on its output level. Knowing the value of x_j, firm j seeks to maximize its gross profits $\pi_j(c_j^M - \delta x_j)$ in (1) over its output level q_j, given its belief q_i about firm i's output level. From the first-order condition for maximizing $\pi_j(c_j^M - \delta x_j)$, we obtain firm j's reaction function:

$$q_j(x_j, q_i) \;=\; \{a - (c_j^M - \delta x_j)\}/2 \;-\; q_i/2. \tag{8}$$

Then, consider firm j's decision on its R&D investment. Given its belief q_i about firm i's output level, firm j seeks to maximize its profits, $\Pi_j(x_j, q_j(x_j, q_i), q_i)$, over its R&D investment x_j:

$$\Pi_j(x_j, q_j(x_j, q_i), q_i) \;=\; \{a - (c_j^M - \delta x_j) - q_i\}^2/4 \;-\; \gamma x_j^2/2. \tag{9}$$

Note that we obtain (9) by substituting (8) into (2). From the first-order condition for maximizing Π_j in (9), we obtain another reaction function of firm j:

$$x_j(q_i) \;=\; \delta(a - c_j^M - q_i)/(2\gamma - \delta^2). \tag{10}$$

Now, using the three reaction functions, (7), (8), and (10), we obtain

$$q_i(x_i) \;=\; \{(\gamma-\delta^2)a-(2\gamma-\delta^2)c_i^M+\gamma c_j^M+\delta(2\gamma-\delta^2)x_i\}/(3\gamma-2\delta^2)$$
$$q_j(x_i) \;=\; \gamma(a+c_i^M-2c_j^M-\delta x_i)/(3\gamma-2\delta^2), \text{ and} \tag{11}$$
$$x_j(x_i) \;=\; \delta(a+c_i^M-2c_j^M-\delta x_i)/(3\gamma-2\delta^2).$$

These are the equilibrium output level of firm i, that of firm j, and the equilibrium R&D investment of firm j, respectively, in the subgame starting after firm i chooses x_i in the first stage.

Next, consider the first stage in which firm i chooses its R&D investment x_i. Having perfect foresight about $\Pi_i(x_i, q_i(x_i), q_j(x_i))$ for any values of x_i, firm i seeks to maximize

$$\Pi_i(x_i, q_i(x_i), q_j(x_i)) \;=\; \{a-q_i(x_i)-q_j(x_i)-(c_i^M-\delta x_i)\}q_i(x_i) \;-\; \gamma x_i^2/2, \tag{12}$$

over its R&D investment x_i. Note that we obtain (12) by substituting $q_i(x_i)$ and $q_j(x_i)$ in (11) into (2). From the first-order condition for maximizing Π_i in (12) with respect to x_i, we obtain firm i's equilibrium R&D investment:[8]

$$x_i^{iD} \;=\; 2\delta(2\gamma-\delta^2)\{(\gamma-\delta^2)a-(2\gamma-\delta^2)c_i^M+\gamma c_j^M\}/\{\gamma(3\gamma-2\delta^2)^2-2\delta^2(2\gamma-\delta^2)^2\}.$$

Note that, henceforth, the superscript *iD* indicates the outcomes of the (*D*, *ND*) subgame or those of the (*ND*, *D*) subgame, depending on which firm is indicated by the letter i in the superscript *iD*.

Now, substituting x_i^{iD} into $q_i(x_i)$, $q_j(x_i)$, and $x_j(x_i)$ in (11), we obtain the firms' equilibrium output levels, q_i^{iD} and q_j^{iD}, and firm j's equilibrium R&D investment, denoted by x_j^{iD}, in the subgame. Next, using the firms' equilibrium R&D investments and their equilibrium output levels, we obtain the firms' equilibrium profits, Π_i^{iD} and Π_j^{iD}, in the subgame.

Lemma 2 summarizes the outcomes of the (*D*, *ND*) subgame if $i = 1$, and those of the (*ND*, *D*) subgame if $i = 2$.

Lemma 2. (*a*) *In the equilibrium of a subgame in which firm i discloses its R&D investment, but firm j does not, for* $i, j = 1, 2$ *with* $i \neq j$, *firm i chooses* $x_i^{iD} = 2\delta(2\gamma-\delta^2)\{(\gamma-\delta^2)a -$

$(2\gamma-\delta^2)c_i^M+\gamma c_j^M\}/Z$ and $q_i^{iD}=\gamma(3\gamma-2\delta^2)\{(\gamma-\delta^2)a-(2\gamma-\delta^2)c_i^M+\gamma c_j^M\}/Z$, where $Z\equiv\gamma(3\gamma-2\delta^2)^2-2\delta^2(2\gamma-\delta^2)^2$. Firm j chooses $x_j^{iD}=\delta W/Z$ and $q_j^{iD}=\gamma W/Z$, where $W\equiv\gamma(3\gamma-2\delta^2)(a+c_i^M-2c_j^M)-2\delta^2\,(2\gamma-\delta^2)(a-c_j^M)$.

(b) Firm i's equilibrium profits are $\Pi_i^{iD}=\gamma\{(\gamma-\delta^2)a-(2\gamma-\delta^2)c_i^M+\gamma c_j^M\}^2/Z$. Firm j's equilibrium profits are $\Pi_j^{iD}=\gamma(2\gamma-\delta^2)W^2/2Z^2$.

We assume that $\gamma(3\gamma-2\delta^2)^2c_1^M>2\delta^2(2\gamma-\delta^2)\{(\gamma-\delta^2)a+\gamma c_2^M\}$, which leads to $(c_i^M-\delta x_i^{iD})>0$ and $(c_j^M-\delta x_j^{iD})>0$, for i, $j=1$, 2 with $i\neq j$. We assume that $(\gamma-\delta^2)>\gamma(c_2^M-c_1^M)/(a-c_2^M)$, which leads to both $x_i^{iD}>0$ and $q_i^{iD}>0$, for $i=1$, 2. We assume that $(3\gamma^2-6\delta^2\gamma+2\delta^4)(a-c_2^M)>\gamma(3\gamma-2\delta^2)\,(c_2^M-c_1^M)$, which leads to both $x_j^{iD}>0$ and $q_j^{iD}>0$, for $i,j=1,2$ with $i\neq j$.[9] Note that, if $c_1^M=c_2^M$, then for all these we only need to assume that $\gamma(9\gamma^2-16\delta^2\gamma+6\delta^4)c_1^M>2\delta^2(2\gamma^2-3\delta^2\gamma+\delta^4)a$.

It is straightforward to see that Π_i^{iD} and Π_j^{iD} in part (*b*), for $i,j=1$, 2 with $i\neq j$, are positive under the assumptions on the parameters given in Section 2.

3.3. The (ND, ND) subgame

In this subgame, each firm chooses its R&D investment, and then chooses its output level, without observing those chosen by the other firm. Note that, when choosing its output level, each firm does not know the other firm's R&D investment, and thus does not know the other firm's new marginal cost.

To solve the (*ND*, *ND*) subgame, we use the solution technique proposed by Baik and Lee (2007). According to their solution technique, the firms' equilibrium R&D investments and their equilibrium output levels in this subgame satisfy the following two requirements. First, each firm's output level is optimal given its own R&D investment and given its belief about the other firm's output level. Second, each firm's R&D investment is optimal given its belief about the other firm's output level and given its own subsequent optimal behavior.

To obtain the firms' equilibrium R&D investments and their equilibrium output levels, we begin by deriving two reaction functions for firm i, for $i = 1, 2$. Working backward, we first consider firm i's decision on its output level. Given its R&D investment x_i, and thus knowing its new marginal costs, $(c_i^M - \delta x_i)$, firm i seeks to maximize its gross profits $\pi_i(c_i^M - \delta x_i)$ in (1) over its output level q_i, taking firm j's output level q_j as given, for $j = 1, 2$ with $i \neq j$. From the first-order condition for maximizing $\pi_i(c_i^M - \delta x_i)$, we obtain firm i's first reaction function:

$$q_i(x_i, q_j) \;=\; \{a - (c_i^M - \delta x_i)\}/2 \;-\; q_j/2. \tag{13}$$

Then, we consider firm i's decision on its R&D investment. Given its belief q_j about firm j's output level, firm i seeks to maximize its profits, $\Pi_i(x_i, q_i(x_i, q_j), q_j)$, over its R&D investment x_i:

$$\Pi_i(x_i, q_i(x_i, q_j), q_j) \;=\; \{a - (c_i^M - \delta x_i) - q_j\}^2/4 \;-\; \gamma x_i^2/2. \tag{14}$$

Note that we obtain (14) by substituting (13) into (2). From the first-order condition for maximizing Π_i in (14), we obtain firm i's second reaction function:

$$x_i(q_j) \;=\; \delta(a - c_i^M - q_j)/(2\gamma - \delta^2). \tag{15}$$

Now, we denote the firms' equilibrium R&D investments and their equilibrium output levels by $(x_1^{ND}, q_1^{ND}, x_2^{ND}, q_2^{ND})$. We obtain them by solving the system of four simultaneous equations, which consists of (13) and (15). Substituting (15) into (13), we have

$$q_1(q_2) \;=\; \gamma(a - c_1^M - q_2)/(2\gamma - \delta^2)$$

and

$$q_2(q_1) \;=\; \gamma(a - c_2^M - q_1)/(2\gamma - \delta^2).$$

By solving this pair of simultaneous equations, we obtain the firms' equilibrium output levels, q_1^{ND} and q_2^{ND}. Next, substituting q_2^{ND} into (15), and q_1^{ND} into (15), we obtain x_1^{ND} and x_2^{ND}, respectively. Finally, substituting the firms' equilibrium R&D investments and their equilibrium output levels into (14), we obtain the firms' equilibrium profits, Π_1^{ND} and Π_2^{ND}, in the (*ND*, *ND*) subgame.

Lemma 3 summarizes the outcomes of the (*ND*, *ND*) subgame.

Lemma 3. (*a*) *In the equilibrium of the* (*ND*, *ND*) *subgame, firm i chooses* $x_i^{ND} = \delta\{(\gamma - \delta^2)a - (2\gamma - \delta^2)c_i^M + \gamma c_j^M\}/\{(2\gamma - \delta^2)^2 - \gamma^2\}$ *and* $q_i^{ND} = \gamma\{(\gamma - \delta^2)a - (2\gamma - \delta^2)c_i^M + \gamma c_j^M\}/\{(2\gamma - \delta^2)^2 - \gamma^2\}$, *for* $i, j = 1, 2$ *with* $i \neq j$.
(*b*) *Firm i's equilibrium profits are* $\Pi_i^{ND} = \gamma(2\gamma - \delta^2)\{(\gamma - \delta^2)a - (2\gamma - \delta^2)c_i^M + \gamma c_j^M\}^2/2\{(2\gamma - \delta^2)^2 - \gamma^2\}^2$, *for* $i, j = 1, 2$ *with* $i \neq j$.

We assume that $(3\gamma c_1^M - \delta^2 a) > 0$ and $(\gamma - \delta^2)(3\gamma c_1^M - \delta^2 a) > \delta^2\gamma(c_2^M - c_1^M)$, which leads to $(c_i^M - \delta x_i^{ND}) > 0$ for $i = 1, 2$. We assume also that $(\gamma - \delta^2) > \gamma(c_2^M - c_1^M)/(a - c_2^M)$, which leads to both $x_i^{ND} > 0$ and $q_i^{ND} > 0$, for $i = 1, 2$. Note that, if $c_1^M = c_2^M$, then for all these we only need to assume that $(3\gamma c_1^M - \delta^2 a) > 0$.

It is straightforward to see that Π_i^{ND} in part (*b*), for $i = 1$, 2, is positive under the assumptions on the parameters given in Section 2.

3.4. Firms' decisions on disclosing their R&D investments

Consider the firms' decisions on disclosing their R&D investments in the first stage of the full game. Each firm announces either the action *D* or the action *ND*. We have four possible combinations of actions resulting from the firms' announcements: (*D*, *D*), (*D*, *ND*), (*ND*, *D*), and (*ND*, *ND*).

Figure 1 illustrates the strategic interaction between the firms in the first stage. For example, if both firms announce *D*, then the combination (*D*, *D*) arises, which will lead to the (*D*, *D*) subgame analyzed in Section 3.1, so that firm *i*'s profits at the end of the game will be Π_i^D, for $i = 1$, 2, in Lemma 1. If firm 1 announces *D* but firm 2 announces *ND*, then the combination (D, ND) arises, which will lead to the (D, ND) subgame analyzed in Section 3.2, so that the firms' profits at the end of the game will be Π_1^{1D} and Π_2^{1D} in Lemma 2.

Which combination arises in equilibrium? To answer this question, we need to compare the firms' profits that will be realized under the four different combinations (see Figure 1). However, under the current assumption that $c_1^M \leq c_2^M$, it is algebraically intractable to do so. Accordingly, to get around this intractableness, we assume henceforth that the firms initially have the same marginal cost c^M of production: $c_1^M = c_2^M = c^M$.[10]

Given that $c_1^M = c_2^M = c^M$, using Lemmas 1, 2, and 3, we obtain the profits of the firms in Figure 1:

$$\Pi_1^D = \Pi_2^D = \gamma(9\gamma - 8\delta^2)(a - c^M)^2/(9\gamma - 4\delta^2)^2,$$

$$\Pi_1^{1D} = \Pi_2^{2D} = \gamma(\gamma - \delta^2)^2(a - c^M)^2/(9\gamma^3 - 20\delta^2\gamma^2 + 12\delta^4\gamma - 2\delta^6),$$

$$\Pi_2^{1D} = \Pi_1^{2D} = \gamma(2\gamma - \delta^2)(3\gamma^2 - 6\delta^2\gamma + 2\delta^4)^2(a - c^M)^2/2(9\gamma^3 - 20\delta^2\gamma^2 + 12\delta^4\gamma - 2\delta^6)^2, \text{ and}$$

$$\Pi_1^{ND} = \Pi_2^{ND} = \gamma(2\gamma - \delta^2)(a - c^M)^2/\, 2(3\gamma - \delta^2)^2.$$

It is tedious but straightforward to obtain that $\Pi_1^D > \Pi_1^{2D}$, $\Pi_2^D > \Pi_2^{1D}$, and $\Pi_i^{iD} > \Pi_i^{ND}$ for $i = 1, 2$. This implies that the action D is each firm's dominant action – that is, each firm's action D yields higher profits than does its action ND, no matter what action the other firm announces. This in turn implies that only the combination (D, D) arises in equilibrium.

Proposition 1. *Given that the firms initially have the same marginal cost of production, only the combination* (D, D) *arises in equilibrium*.

The result that firm i announces in the first stage that it will disclose its R&D investment, regardless of the action it expects firm j to choose, for $i, j = 1, 2$ with $i \neq j$, can be explained as follows.

Consider first the case where firm *i* expects firm *j* to choose *D*. Firm *i* has two options: either to choose *D* or to choose *ND*. If it chooses *D*, both firms will disclose their R&D investments. Then, firm *i* will compete against firm *j* in symmetric environments in the subsequent stages. By contrast, if firm *i* chooses *ND*, only firm *j* will disclose its R&D investment, and thus firm *j* will exercise strategic leadership in choosing an R&D investment. Then, firm *j* as the leader will choose a greater R&D investment than firm *i*, the follower.[11] As a result of this, firm *i*'s new marginal cost will be greater than firm *j*'s new marginal cost, which implies that firm *i*'s output level will be smaller than firm *j*'s output level. Consequently, firm *i* will end up with lower profits, as compared to its choosing *D*. Hence, given firm *j*'s action *D*, firm *i* chooses *D*.

Next, consider the case where firm *i* expects firm *j* chooses *ND*. In this case, too, firm *i* is better off by choosing *D* rather than *ND*. This is supported by the following explanation. With firm *j*'s action *ND* and its own action *D*, firm *i* will exercise strategic leadership in choosing an R&D investment. Indeed, it will enjoy a first-mover advantage by disclosing its R&D investment before firm *j* chooses its R&D investment. However, if firm *i* chooses *ND* instead of *D*, it will not have the strategic leadership and play a simultaneous-move game against firm *j*, choosing two sequential actions without observing those chosen by firm *j*, which will result in smaller profits to firm *i*.

Baik and Lee (2012) study a rent-seeking contest in which two groups compete to win a rent, and each group has the option of disclosing or not its sharing-rule information. Interestingly, they show that the case where both groups disclose their sharing-rule information never arises in equilibrium. Baik and Lee (2020) study both a quantity-setting duopoly and a price-setting duopoly in which each firm consists of an owner and a manager, and has the option of disclosing or not its contract information between the owner and the manager. They show in both models that the firms disclose their contract information.

3.5. The outcomes of the entire game

Let the superscript * denote the equilibrium values of variables. Given that $c_1^M = c_2^M = c^M$, using Proposition 1 and Lemma 1, we obtain the following outcomes of the game. First, both firms announce in the first stage that they will disclose their R&D investments to the public. Second, firm *i*, for $i = 1, 2$, chooses and discloses its R&D investment, $x_i^* = 4\delta(a - c^M)/(9\gamma - 4\delta^2)$. Third, firm *i* chooses its output level, $q_i^* = 3\gamma(a - c^M)/(9\gamma - 4\delta^2)$. Finally, firm *i*'s profits are $\Pi_i^* = \gamma(9\gamma - 8\delta^2)(a - c^M)^2/(9\gamma - 4\delta^2)^2$.

Performing comparative statics of these outcomes with respect to each of the parameters, respectively, we obtain the following (comparative statics) results.

Remark 1. (*a*) *As the size a of the market increases*, *the investment* x_i^*, *the output level* q_i^*, *and the profits* Π_i^* *all increase*. (*b*) *As the initial marginal cost* c_M *of production* decreases, *the investment* x_i^*, *the output level* q_i^*, *and the profits* Π_i^* *all increase*. (*c*) *As the parameter* δ *increases*, *the investment* x_i^* *and the output level* q_i^* *increase while the profits* Π_i^* *decrease*. (*d*) *As the parameter* γ *increases*, *the investment* x_i^* *and the output level* q_i^* *decrease while the profits* Π_i^* *increase*.

Parts (*a*) and (*b*) make intuitive sense. An increase in the size *a* of the market or a *decrease* in the initial marginal cost c_M of production, *ceteris paribus*, enables the firms to earn more profits, which leads to the firms increasing their R&D investments. This increase in the investment x_i^*, in turn, decreases (further) firm *i*'s new marginal cost, which leads to the firm choosing a greater output level and earning more profits.[12]

Part (*c*) can be explained as follows. An increase in the parameter δ, *ceteris paribus*, decreases each firm's new marginal cost, and thus increases its profits. This leads to each firm increasing its R&D investment. Next, this increase in the investment x_i^* decreases further firm *i*'s new marginal cost. As a result, firm *i*'s output level q_i^* increases. However, firm *i*'s profits Π_i^*

decrease because the cost $\gamma(x_i^*)^2/2$ of its R&D investment increases more than do the gross profits $\pi_i^*(c^M - \delta x_i^*)$ for firm i.

Part (d) can be explained as follows. An increase in the parameter γ, *ceteris paribus*, decreases each firm's R&D investment because it increases the cost of making an R&D investment. Next, this decrease in the investment x_i^* increases firm i's new marginal cost. As a result, firm i's output level q_i^* decreases. However, firm i's profits Π_i^* increase because the cost $\gamma(x_i^*)^2/2$ of its R&D investment decreases more than do the gross profits $\pi_i^*(c^M - \delta x_i^*)$ for firm i.

4. Price-setting duopoly with R&D competition

Consider a price-setting duopoly with differentiated products in which two profit-maximizing firms, 1 and 2, make R&D investments to reduce their production costs. Each firm first announces publicly whether it will disclose the amount of its R&D investment to the public. Then, each firm makes an R&D investment to reduce its marginal cost of production, and discloses the R&D amount if the firm announced to do so. Finally, the firms produce their products at the resulting reduced costs, and compete in prices.

The R&D cost function of firm i, for $i = 1, 2$, is given by $K(x_i) = \gamma x_i^2/2$, where $\gamma \geq 1$, $x_i > 0$, and x_i denotes the R&D investment that firm i makes. Given its constant marginal cost of c_i, the cost function of firm i is given by $V_i(q_i) = c_i q_i$ for all $q_i \in R_+$, where q_i denotes firm i's output level. Note that we abuse notation by using the same notation as in Section 2.

We assume that, before undertaking their R&D investments, the firms have the same marginal cost c^M of production, which is publicly known. When undertaking its R&D investment, each firm knows for sure how much marginal cost it can reduce by undertaking the R&D investment – that is, it is certain about its new marginal cost resulting from the R&D investment. Let c_i, for $i = 1, 2$, denote firm i's new marginal cost which is deterministically determined by its R&D investment x_i. We assume that $c_i = c^M - \delta x_i$, where $0 < \delta < 0.75$. We assume also that c^M/δ is sufficiently large that $(c^M - \delta x_i) > 0$ in a relevant range of firm i's R&D investments.

When the firms choose their prices, each firm knows its own new marginal cost, but cannot directly observe the other firm's new marginal cost. Specifically, each firm knows the other firm's new marginal cost only if the other firm disclosed its R&D investment. However, in the case where the other firm did not disclose its R&D investment, each firm "knows" the other firm's new marginal cost under its belief about the other firm's R&D investment.

The market demand function facing firm i is given by

$$q_i \;=\; s \;-\; p_i \;+\; kp_j,$$

for $i, j = 1, 2$ with $i \neq j$, where q_i denotes the quantity of firm i's product demanded, p_i denotes firm i's price, p_j denotes firm j's price, and s and k are positive constants. We assume that the quantity of firm i's product demanded is more responsive to a change in firm i's price than to the same change in firm j's price: In terms of symbols, $0 < k < 1$. We assume also that $0 < c^M < s/(1-k)$.

We formally consider the following game. First, each firm decides independently whether it will disclose its R&D investment to the public. The firms simultaneously announce and commit to their decisions before making their R&D investments. Next, each firm independently makes a cost-reducing R&D investment – that is, firm i, for $i = 1, 2$, chooses the value of x_i – and discloses the R&D investment if the firm announced to do so. Finally, the firms choose their prices simultaneously and independently. (We will be more specific about the game in Section 5 – in particular, about the timing of the firms' R&D investment decisions, and about each firm's information on the other firm's new marginal cost.)

Let $\psi_i(c_i)$ denote firm i's gross profits – computed at the time when the firms choose their prices – given its new marginal cost of c_i. Then the gross profit function for firm i is

$$\psi_i(c_i) \;=\; (p_i - c_i)\,(s - p_i + kp_j), \tag{16}$$

for $i, j = 1, 2$ with $i \neq j$, where p_j denotes firm i's belief about firm j's price.

Let $\Psi_i(x_i)$ denote firm i's profits from choosing an R&D investment of x_i – computed at the time when the firms choose their R&D investments – given its price p_i and its belief that firm j will quote p_j. Then the profit function for firm i is

$$\Psi_i(x_i) \ = \ \psi_i(c^M - \delta x_i) \ - \ \gamma x_i^2/2, \tag{17}$$

where $\psi_i(c^M - \delta x_i)$ denotes the gross profits for firm i at its new marginal cost of $(c^M - \delta x_i)$ which results from its R&D investment x_i.

We end this section by assuming that all of the above is common knowledge between the firms.

5. The equilibrium decisions of the firms

Working backward, we first analyze the four subgames which start after the firms announce publicly whether they will disclose their R&D investments to the public, and then consider the firms' decisions, in the first stage, on disclosing their R&D investments.

5.1. The (*D*, *D*) *subgame*

To obtain a subgame-perfect equilibrium *outcome* of this subgame, we work backward. Consider first the (x_1, x_2) subgame in which the firms choose their prices, each knowing the R&D investments, x_1 and x_2, and thus the new marginal costs, $(c^M - \delta x_1)$ and $(c^M - \delta x_2)$. Firm i seeks to maximize its gross profits $\psi_i(c^M - \delta x_i)$ in (16) over its price p_i, taking the price p_j of firm j as given, for i, $j = 1$, 2 with $i \neq j$. From the first-order condition for maximizing $\psi_i(c^M - \delta x_i)$, we obtain firm i's reaction function:

$$p_i(x_i, p_j) \ = \ \{s + (c^M - \delta x_i)\}/2 \ + \ kp_j/2. \tag{18}$$

It is straightforward to check that the second-order condition for maximizing $\psi_i(c^M - \delta x_i)$ is satisfied.[13]

Using those reaction functions in (18), we obtain the Nash equilibrium of the (x_1, x_2) subgame:

$$p_i(x_1, x_2) \ = \ \{(2+k)s + 2(c^M - \delta x_i) + k(c^M - \delta x_j)\}/(4-k^2) \tag{19}$$

for $i, j = 1, 2$ with $i \neq j$. Let $\psi_i(x_1, x_2)$, for $i = 1, 2$, denote firm i's gross profits at the Nash equilibrium of the (x_1, x_2) subgame. Then, substituting the equilibrium prices in (19) into $\psi_i(c^M - \delta x_i)$ in (16), we obtain

$$\psi_i(x_1, x_2) \ = \ \{(2+k)s - (2-k^2)(c^M - \delta x_i) + k(c^M - \delta x_j)\}^2/(4-k^2)^2. \tag{20}$$

Next, consider the stage in which firms 1 and 2 choose their R&D investments, x_1 and x_2, respectively. In this stage, each firm has perfect foresight about both $\psi_1(x_1, x_2)$ and $\psi_2(x_1, x_2)$ in (20) for any values of x_1 and x_2. Given its belief about the other firm's R&D investment, firm i, for $i = 1, 2$, seeks to maximize its profits, $\Psi_i(x_1, x_2)$, over its R&D investment x_i:

$$\Psi_i(x_1, x_2) \ = \ \psi_i(x_1, x_2) \ - \ \gamma x_i^2/2. \tag{21}$$

From the first-order condition for maximizing (21), we obtain firm i's reaction function:

$$x_i(x_j) \ = \ 2\delta(2-k^2)\{(2+k)s - (2-k-k^2)c^M - \delta k x_j\}/\{\gamma(4-k^2)^2 - 2\delta^2(2-k^2)^2\}$$

for $i, j = 1, 2$ with $i \neq j$. Using these two reaction functions, we obtain firm i's R&D investment, x_i^D, which is specified in the subgame-perfect equilibrium of the (D, D) subgame:

$$x_i^D \ = \ 2\delta(2-k^2)\{s - (1-k)c^M\}/\{\gamma(2-k)(4-k^2) - 2\delta^2(1-k)(2-k^2)\}.$$

Now, substituting the firms' equilibrium R&D investments, x_1^D and x_2^D, into $p_1(x_1, x_2)$ and $p_2(x_1, x_2)$ in (19), we obtain the firms' equilibrium prices, p_1^D and p_2^D, respectively. Next, substituting x_1^D and x_2^D into $\Psi_1(x_1, x_2)$ and $\Psi_2(x_1, x_2)$ in (21), we obtain the firms' equilibrium profits, Ψ_1^D and Ψ_2^D, in the (D, D) subgame.

Lemma 4 summarizes the outcomes of the (D, D) subgame.

Lemma 4. (a) *In the equilibrium of the* (D, D) *subgame*, *firm* i, *for* $i = 1, 2$, *chooses* $x_i^D = 2\delta(2-k^2)\{s-(1-k)c^M\}/\{\gamma(2-k)(4-k^2)-2\delta^2(1-k)(2-k^2)\}$ *and* $p_i^D = \{\gamma(4-k^2)s - 2\delta^2(2-k^2)s + \gamma(4-k^2)c^M\}/\{\gamma(2-k)(4-k^2)-2\delta^2(1-k)(2-k^2)\}$.
(b) *The firms' equilibrium profits are* $\Psi_1^D = \Psi_2^D = \{\gamma^2(4-k^2)^2 - 2\delta^2\gamma(2-k^2)^2\}\{s-(1-k)c^M\}^2/\{\gamma(2-k)(4-k^2)-2\delta^2(1-k)(2-k^2)\}^2$.

We assume that $\gamma(4-k^2)(2-k)c^M > 2\delta^2(2-k^2)s$, which leads to $(c^M - \delta x_i^D) > 0$ for $i = 1, 2$. It is straightforward to see that $x_i^D > 0$, $p_i^D > 0$, and $\Psi_i^D > 0$, under the assumptions on the parameters given in Section 4.

5.2. The (D, ND) *subgame and the* (ND, D) *subgame*

Consider a subgame in which firm i discloses its R&D investment to the public, but firm j does not, for $i, j = 1, 2$ with $i \neq j$. Note that the (D, ND) subgame arises if $i = 1$, and the (ND, D) subgame arises if $i = 2$.

We assume that firm j chooses its R&D investment after observing firm i's R&D investment. This subgame is then described as follows. First, firm i chooses and discloses its R&D investment. Next, after observing firm i's R&D investment, firm j chooses its R&D investment, but does not disclose it. Finally, both firms choose their prices simultaneously and independently. Note that, at this stage, firm i knows only its own new marginal cost, but firm j knows the new marginal costs of both firms.

We solve the subgame by viewing it as the following two-stage game. In the first stage, firm i chooses its R&D investment x_i, and discloses it to the public. In the second stage, knowing the value of x_i and thus knowing its new marginal cost, firm i chooses its price without observing firm j's R&D investment or its price; firm j chooses its R&D investment, and then (knowing both firms' new marginal costs) chooses its price without observing firm i's price.

To solve this two-stage game, we work backward. In the second stage, knowing the value of x_i, firm i seeks to maximize its gross profits $\psi_i(c^M - \delta x_i)$ in (16) over its price p_i, given its belief p_j about firm j's price. From the first-order condition for maximizing $\psi_i(c^M - \delta x_i)$, we obtain firm i's reaction function:

$$p_i(x_i, p_j) \;=\; \{s + (c^M - \delta x_i)\}/2 \;+\; kp_j/2. \tag{22}$$

Next, we obtain firm j's two reaction functions in the second stage. First consider firm j's decision on its price. Knowing the value of x_j, firm j seeks to maximize its gross profits $\psi_j(c^M - \delta x_j)$ in (16) over its price p_j, given its belief p_i about firm i's price. From the first-order condition for maximizing $\psi_j(c^M - \delta x_j)$, we obtain firm j's reaction function:

$$p_j(x_j, p_i) \;=\; \{s + (c^M - \delta x_j)\}/2 \;+\; kp_i/2. \tag{23}$$

Then, consider firm j's decision on its R&D investment. Given its belief p_i about firm i's price, firm j seeks to maximize its profits, $\Psi_j(x_j, p_j(x_j, p_i), p_i)$, over its R&D investment x_j:

$$\Psi_j(x_j, p_j(x_j, p_i), p_i) \;=\; \{s - (c^M - \delta x_j) + kp_i\}^2/4 \;-\; \gamma x_j^2/2. \tag{24}$$

Note that we obtain (24) by substituting (23) into (17). From the first-order condition for maximizing Ψ_j in (24), we obtain another reaction function of firm j:

$$x_j(p_i) \;=\; \delta(s - c^M + kp_i)/(2\gamma - \delta^2). \tag{25}$$

Now, using the three reaction functions, (22), (23), and (25), we obtain

$$\begin{aligned} p_i(x_i) \;&=\; \{(2\gamma - \delta^2)(s + c^M - \delta x_i) + (\gamma - \delta^2)ks + \gamma kc^M\}/\{2(2\gamma - \delta^2) - (\gamma - \delta^2)k^2\} \\ p_j(x_i) \;&=\; \{(\gamma - \delta^2)(2 + k)s + 2\gamma c^M + k(\gamma - \delta^2)(c^M - \delta x_i)\}/\{2(2\gamma - \delta^2) - (\gamma - \delta^2)k^2\}, \end{aligned} \tag{26}$$

and

$$x_j(x_i) \;=\; \delta\{(2 + k)s + (k^2 - 2)c^M + k(c^M - \delta x_i)\}/\{2(2\gamma - \delta^2) - (\gamma - \delta^2)k^2\}.$$

These are the equilibrium price of firm i, that of firm j, and the equilibrium R&D investment of firm j, respectively, in the subgame starting after firm i chooses x_i in the first stage.

Next, consider the first stage in which firm i chooses its R&D investment x_i. Having perfect foresight about $\Psi_i(x_i, p_i(x_i), p_j(x_i))$ for any values of x_i, firm i seeks to maximize

$$\Psi_i(x_i, p_i(x_i), p_j(x_i)) \;=\; \{p_i(x_i) - (c^M - \delta x_i)\}\{s - p_i(x_i) + kp_j(x_i)\} \;-\; \gamma x_i^2/2, \qquad (27)$$

over its R&D investment x_i. Note that we obtain (27) by substituting $p_i(x_i)$ and $p_j(x_i)$ in (26) into (17). From the first-order condition for maximizing Ψ_i in (27) with respect to x_i, we obtain firm i's equilibrium R&D investment:

$$x_i^{iD} \;=\; 2\delta\{(2\gamma - \delta^2) - (\gamma - \delta^2)k^2\}\{\gamma(2 + k) - \delta^2(1 + k)\}\{s - (1 - k)c^M\}/ \qquad (28)$$
$$[\gamma\{2(2\gamma - \delta^2) - (\gamma - \delta^2)k^2\}^2 - 2\delta^2\{(2\gamma - \delta^2) - (\gamma - \delta^2)k^2\}^2].$$

Now, substituting x_i^{iD} in (28) into $p_i(x_i)$, $p_j(x_i)$, and $x_j(x_i)$ in (26), we obtain the firms' equilibrium prices, p_i^{iD} and p_j^{iD}, and firm j's equilibrium R&D investment, denoted by x_j^{iD}, in the subgame. Next, using the firms' equilibrium R&D investments and their equilibrium prices, we obtain the firms' equilibrium profits, Ψ_i^{iD} and Ψ_j^{iD}, in the subgame.

Lemma 5 summarizes the outcomes of the (D, ND) subgame if $i = 1$, and those of the (ND, D) subgame if $i = 2$.

Lemma 5. (a) *In the equilibrium of a subgame in which firm i discloses its R&D investment, but firm j does not, for i, j* $= 1, 2$ *with* $i \neq j$, *firm i chooses* $x_i^{iD} = 2G\{\gamma(2 + k) - \delta^2(1 + k)\}\{s - (1 - k)c^M\}/(\gamma H^2 - 2G^2)$ *and* $p_i^{iD} = [(\gamma - \delta^2)\{4\gamma - 2\delta^2 - (\gamma - 2\delta^2)k^2\}\{2\gamma - \delta^2 + (\gamma - \delta^2)k\}s + \gamma\{H(2\gamma + \gamma k - \delta^2) - 2\delta Gk\}c^M]/(\gamma H^2 - 2G^2)$, *where* $G \equiv \delta\{2\gamma - \delta^2 - (\gamma - \delta^2)k^2\}$ *and* $H \equiv 4\gamma - 2\delta^2 - (\gamma - \delta^2)k^2$. *Firm j chooses* $x_j^{iD} = \delta\{\gamma H(2 + k) - 2\delta G(1 + k)\}\{s - (1 - k)c^M\}/(\gamma H^2 - 2G^2)$ *and* $p_j^{iD} = [(\gamma - \delta^2)\{\gamma H(2 + k) - 2\delta G(1 + k)\}s + \gamma\{H(2\gamma + \gamma k - \delta^2 k) - 2\delta G\}c^M]/(\gamma H^2 - 2G^2)$.

(b) *Firm i's equilibrium profits are* $\Psi_i^{iD} = \gamma\{2\gamma - \delta^2 + (\gamma - \delta^2)k\}^2\{s - (1-k)c^M\}^2/(\gamma H^2 - 2G^2)$. *Firm j's equilibrium profits are* $\Psi_j^{iD} = \gamma(2\gamma - \delta^2)\{\gamma H(2+k) - 2\delta G(1+k)\}^2\{s - (1-k)c^M\}^2/2(\gamma H^2 - 2G^2)^2$.

We assume that $\{\gamma H(4\gamma - \delta^2 k - \gamma k^2) - 2\delta\gamma G(2 - k^2)\}c^M > \delta^2\{\gamma H(2+k) - 2\delta G(1+k)\}s$, which leads to $(c^M - \delta x_i^{iD}) > 0$ and $(c^M - \delta x_j^{iD}) > 0$, for i, $j = 1$, 2 with $i \neq j$. It is straightforward to see that $x_i^{iD} > 0$, $x_j^{iD} > 0$, $p_i^{iD} > 0$, $p_j^{iD} > 0$, $\Psi_i^{iD} > 0$, and $\Psi_j^{iD} > 0$, for $i, j = 1$, 2 with $i \neq j$, under the assumptions on the parameters given in Section 4.

5.3. The (*ND*, *ND*) *subgame*

According to the solution technique proposed by Baik and Lee (2007), the firms' equilibrium R&D investments and their equilibrium prices in this subgame satisfy the following two requirements. First, each firm's price is optimal given its own R&D investment and given its belief about the other firm's price. Second, each firm's R&D investment is optimal given its belief about the other firm's price and given its own subsequent optimal behavior.

To obtain the firms' equilibrium R&D investments and their equilibrium prices, we begin by deriving two reaction functions for firm i, for $i = 1, 2$. Working backward, we first consider firm i's decision on its price. Given its R&D investment x_i, and thus knowing its new marginal costs, $(c^M - \delta x_i)$, firm i seeks to maximize its gross profits $\psi_i(c^M - \delta x_i)$ in (16) over its price p_i, taking firm j's price p_j as given, for $j = 1$, 2 with $i \neq j$. From the first-order condition for maximizing $\psi_i(c^M - \delta x_i)$, we obtain firm i's first reaction function:

$$p_i(x_i, p_j) \;=\; \{s + (c^M - \delta x_i)\}/2 \;+\; kp_j/2. \tag{29}$$

Then, we consider firm i's decision on its R&D investment. Given its belief p_j about firm j's price, firm i seeks to maximize its profits, $\Psi_i(x_i, p_i(x_i, p_j), p_j)$, over its R&D investment x_i:

$$\Psi_i(x_i, p_i(x_i, p_j), p_j) \;=\; \{s - (c^M - \delta x_i) + kp_j\}^2/4 \;-\; \gamma x_i^2/2. \tag{30}$$

Note that we obtain (30) by substituting (29) into (17). From the first-order condition for maximizing Ψ_i in (30), we obtain firm i's second reaction function:

$$x_i(p_j) = \delta(s - c^M + kp_j)/(2\gamma - \delta^2). \tag{31}$$

Now, we denote the firms' equilibrium R&D investments and their equilibrium prices by $(x_1^{ND}, p_1^{ND}, x_2^{ND}, p_2^{ND})$. We obtain them by solving the system of four simultaneous equations, which consists of (29) and (31). Substituting (31) into (29), we have

$$p_1(p_2) = \{\gamma c^M + (\gamma - \delta^2)(s + kp_2)\}/(2\gamma - \delta^2)$$

and

$$p_2(p_1) = \{\gamma c^M + (\gamma - \delta^2)(s + kp_1)\}/(2\gamma - \delta^2).$$

By solving this pair of simultaneous equations, we obtain the firms' equilibrium prices, p_1^{ND} and p_2^{ND}. Next, substituting p_2^{ND} into (31), and p_1^{ND} into (31), we obtain x_1^{ND} and x_2^{ND}, respectively. Finally, substituting the firms' equilibrium R&D investments and their equilibrium prices into (30), we obtain the firms' equilibrium profits, Ψ_1^{ND} and Ψ_2^{ND}, in the (*ND*, *ND*) subgame.

Lemma 6 summarizes the outcomes of the (*ND*, *ND*) subgame.

Lemma 6. (*a*) *In the equilibrium of the* (*ND*, *ND*) *subgame*, *firm* i, *for* $i = 1, 2$, *chooses* $x_i^{ND} = \delta\{s - (1-k)c^M\}/\{\gamma(2-k) - \delta^2(1-k)\}$ *and* $p_i^{ND} = (\gamma s - \delta^2 s + \gamma c^M)/\{\gamma(2-k) - \delta^2(1-k)\}$. (*b*) *The firms' equilibrium profits are* $\Psi_1^{ND} = \Psi_2^{ND} = \gamma(2\gamma - \delta^2)\{s - (1-k)c^M\}^2/2\{\gamma(2-k) - \delta^2(1-k)\}^2$.

We assume that $\gamma(2-k)c^M > \delta^2 s$, which leads to $(c^M - \delta x_i^{ND}) > 0$ for $i = 1, 2$. It is straightforward to see that $x_i^{ND} > 0$, $p_i^{ND} > 0$, and $\Psi_i^{ND} > 0$, under the assumptions on the parameters given in Section 4.

5.4. Firms' decisions on disclosing their R&D investments

Consider the firms' decisions on disclosing their R&D investments in the first stage of the full game. Each firm announces either the action *D* or the action *ND*. We have four possible combinations of actions resulting from the firms' announcements: (*D*, *D*), (*D*, *ND*), (*ND*, *D*), and (*ND*, *ND*).

Figure 2 illustrates the strategic interaction between the firms in the first stage. Simply speaking, it shows the profits of the firms, reported in Lemmas 4 through 6, which will be realized under the four possible combinations.

Which combination arises in equilibrium? To answer this question, we need to compare the firms' profits that will be realized under the four different combinations (see Figure 2). However, it is algebraically intractable to do so with general values of the parameters of γ and k. Accordingly, to get around this intractableness, we assume henceforth that $\gamma = 1$, in which case the R&D cost function of firm i, for $i = 1, 2$, is given by $K(x_i) = x_i^2/2$.

Given that $\gamma = 1$, using Lemmas 5 and 6, we obtain that $\Psi_i^{iD} > \Psi_i^{ND}$ for $i = 1, 2$. This implies that the combination (*ND*, *ND*) does not arise in equilibrium. Next, given that $\gamma = 1$, it is algebraically intractable to compare the profits, Ψ_i^D and Ψ_i^{jD}, for $i, j = 1, 2$ with $i \neq j$, with general values of the parameter k (see Lemmas 4 and 5). However, on the basis of our extensive numerical investigation, we conclude that $\Psi_i^D > \Psi_i^{jD}$, regardless of the size of the product differentiation parameter k. This conclusion then implies that the combination (*D*, *D*) arises in equilibrium, whereas neither the combination (*D*, *ND*) nor the combination (*ND*, *D*) arises in equilibrium.

Proposition 2. *Given that* $\gamma = 1$, *only the combination* (*D*, *D*) *arises in equilibrium.*

Proposition 2 says that the firms disclose their R&D investments to the public in equilibrium. The intuition behind Proposition 2 is similar to that for Proposition 1, and therefore is omitted.

5.5. The outcomes of the entire game

Let the superscript ** denote the equilibrium values of variables. Given that $\gamma = 1$, using Proposition 2 and Lemma 4, we obtain the following outcomes of the game. First, both firms announce in the first stage that they will disclose their R&D investments to the public. Second, firm i, for $i = 1, 2$, chooses and discloses its R&D investment, $x_i^{**} = 2\delta(2 - k^2)\{s - (1 - k)c^M\}/\{(2 - k)(4 - k^2) - 2\delta^2(1 - k)(2 - k^2)\}$. Third, firm i chooses its price, $p_i^{**} = \{(4 - k^2)s - 2\delta^2(2 - k^2)s + (4 - k^2)c^M\}/\{(2 - k)(4 - k^2) - 2\delta^2(1 - k)(2 - k^2)\}$. Finally, firm i's profits are $\Psi_i^{**} = \{(4 - k^2)^2 - 2\delta^2(2 - k^2)^2\}\{s - (1 - k)c^M\}^2/\{(2 - k)(4 - k^2) - 2\delta^2(1 - k)(2 - k^2)\}^2$.

Performing comparative statics of these outcomes with respect to each of the parameters, respectively, we obtain the following (comparative statics) results.

Remark 2. (a) *As the size s of the market increases*, *the investment* x_i^{**}, *the price* p_i^{**}, *and the profits* Ψ_i^{**} *all increase*. (b) *As the initial marginal cost* c_M *of production* decreases, *the investment* x_i^{**} *and the profits* Ψ_i^{**} *increase while the price* p_i^{**} *decreases*. (c) *As the parameter* δ *increases*, *the investment* x_i^{**} *and the profits* Ψ_i^{**} *increase while the price* p_i^{**} *decreases*. (d) *As the parameter k increases*, *the price* p_i^{**} *and the profits* Ψ_i^{**} *increase*.

Part (a) can be explained as follows. An increase in the size s of the market, *ceteris paribus*, enables the firms to earn more profits, which leads to the firms increasing their R&D investments. This increase in the investment x_i^{**}, in turn, decreases firm i's new marginal cost, which leads to the firm choosing a higher price and earning more profits.[14]

Parts (b) can be explained as follows. A *decrease* in the initial marginal cost c_M of production, *ceteris paribus*, enables the firms to earn more profits, which leads to the firms increasing their R&D investments. This increase in the investment x_i^{**}, in turn, decreases further firm i's new marginal cost, which leads to the firm choosing a lower price.[15] However, firm i's profits Ψ_i^{**} increase because the gross profits $\psi_i^{**}(c^M - \delta x_i^{**})$ for firm i increase more than does the cost $(x_i^{**})^2/2$ of its R&D investment.

Part (c) can be explained as follows. An increase in the parameter δ, *ceteris paribus*, decreases each firm's new marginal cost, and thus increases its profits. This leads to each firm increasing its R&D investment. Next, this increase in the investment x_i^{**} decreases further firm i's new marginal cost. As a result, firm i's price p_i^{**} decreases. However, firm i's profits Ψ_i^{**} increase because the gross profits $\psi_i^{**}(c^M - \delta x_i^{**})$ for firm i increase more than does the cost $(x_i^{**})^2/2$ of its R&D investment.

Part (d) says that, as the parameter k increases, each firm chooses a higher price and earns more profits. Due to computational complexity involved, we cannot algebraically determine the sign of $\partial x_i^{**}/\partial k$ – that is, the effect of increasing the value of the parameter k on the investment x_i^{**}. However, on the basis of our extensive numerical investigation, we conclude that the sign of $\partial x_i^{**}/\partial k$ may always be positive; or it may be positive at a small or large value of k, but negative at a "very large" value of k.

6. Conclusions

We have studied the quantity-setting duopoly and the price-setting duopoly in which each firm has the option of disclosing or not its cost-reducing R&D investment. We have formally considered the following game. In the first stage, each firm decides and announces whether it will disclose its R&D investment to the public. Next, each firm chooses – and discloses if it announced to do so – its R&D investment. Finally, the firms choose their output levels [prices] simultaneously and independently.

Both in the quantity-setting duopoly and in the price-setting duopoly, when choosing its R&D investment, each firm knows how much marginal cost it can reduce by undertaking the R&D investment. When the firms choose their output levels [prices], each firm knows the other firm's new marginal cost only if the other firm disclosed its R&D investment.

In the quantity-setting duopoly, assuming that the firms initially have the same marginal cost of production, we have first shown that, in equilibrium, each firm discloses its R&D investment. Then, we have obtained the outcomes of the game, and have examined how these outcomes respond when each of the parameters changes, *ceteris paribus*.

In the price-setting duopoly, assuming that the firms initially have the same marginal cost of production and that $\gamma = 1$, we have first shown that, in equilibrium, each firm discloses its R&D investment. Then, we have obtained the outcomes of the game, and have performed comparative statics of these outcomes with respect to each of the parameters, respectively.

In the duopoly models we have considered in this paper, we have assumed for tractability that, when undertaking its R&D investment, each firm knows for sure how much marginal cost it can reduce by undertaking the R&D investment – that is, each firm's new marginal cost is deterministically determined by its R&D investment. If computationally tractable, it would be interesting to consider duopoly models in which, when making its R&D investment, each firm is uncertain about how much marginal cost it can reduce by undertaking the R&D investment – that is, models in which each firm's new marginal cost is probabilistically determined by its R&D investment (see, for example, Baik and Kim, 2020). We leave these modifications for future research.

Footnotes

1. It might be more interesting to consider a model in which, when making its R&D investment, each firm is uncertain about its R&D outcome; its new production cost is probabilistically determined before competing in the market. However, it seems to be intractable to analyze such a model with ex ante uncertainty regarding R&D outcomes.

2. Quadratic R&D cost functions are extensively used in the R&D literature. See, for example, Haaland and Kind (2008), Tishler and Milstein (2009), Bourreau and Dogan (2010), Ishida et al. (2011), Lin and Zhou (2013), Milliou and Pavlou (2013), Chang and Ho (2014), and Baik and Kim (2020).

3. As will see in Section 3.4, we cannot complete our analysis without assuming that $c_1^M = c_2^M$. However, for the reader's benefit, we attempt to analyze the model as far as possible under the less restrictive constraint: $c_1^M \leq c_2^M$.

4. Milliou and Pavlou (2013), Chang and Ho (2014), and Ishii (2017) assume that the R&D process is deterministic.

5. Under the assumptions on the parameters given in Section 2, the second-order condition is satisfied for every maximization problem in Section 3.

6. Alternatively, we may assume that firm *j* chooses its R&D investment before or without observing firm *i*'s R&D investment. This subgame is then described as follows. First, each firm chooses its R&D investment without observing the other firm's R&D investment. Next, firm *i* discloses its R&D investment to the public, but firm *j* does not disclose its R&D investment. As a result, firm *i* knows only its own new marginal cost, whereas firm *j* knows both firms' new marginal costs. Finally, both firms choose their output levels simultaneously and independently.

To solve the subgame, we can use the solution technique introduced by Baik and Lee (2024). With the alternative assumption about the timing of the firms' first moves, however, we believe that we obtain the same main results as those with the current assumption.

7. The solution technique used in Sections 3.2 and 5.2 is discussed in detail in Baik and Lee (2012).

8. The second-order condition for maximizing Π_i in (12) is satisfied since $\partial^2\Pi_i/\partial x_i^2 = 2\{\delta(2\gamma - \delta^2)/(3\gamma - 2\delta^2)\}^2 - \gamma < 0$ under the assumptions on the parameters. Note that $\partial^2\Pi_i/\partial x_i^2$ increases as the parameter δ increases, but decreases as the parameter γ increases.

9. The value of $(3\gamma^2 - 6\delta^2\gamma + 2\delta^4)$ is always positive under the assumptions on the parameters. Note that it decreases as the parameter δ increases, but increases as the parameter γ increases.

10. It is straightforward to see that, if $c_1^M = c_2^M = c^M$, then Lemmas 1 through 3 hold if and only if $c^M\gamma(9\gamma^2 - 16\delta^2\gamma + 6\delta^4) > 2a\delta^2 \ (2\gamma^2 - 3\delta^2\gamma + \delta^4)$ (see the paragraph below each lemma).

11. Note that the follower firm's R&D reaction function is decreasing in the leader firm's R&D investment (see (11)).

12. This can be explained graphically in terms of the firms' reaction functions (see expression (3)). First, note that the firms' reaction functions are downward sloping in the q_1q_2-space, and the firms choose their output levels at the intersection of their reaction functions. Next, an increase in a or a decrease in c_M, together with the resulting increase in x_i^*, shifts the reactions functions outward. This entails that the firms choose greater output levels.

13. Under the assumptions on the parameters given in Section 4, the second-order condition is satisfied for every maximization problem in Section 5.

14. This can be explained graphically in terms of the firms' reaction functions (see expression (18)). First, note that the firms' reaction functions are upward sloping in the p_1p_2-space, and the firms choose their prices at the intersection of their reaction functions. Next, an increase in s, together with the resulting increase in x_i^{**}, shifts the reactions functions outward. This entails that the firms choose higher prices.

15. Graphically, an decrease in c_M, together with the resulting increase in x_i^{**}, shifts the firms' reactions functions inward (see expression (18)). This entails that the firms choose lower prices.

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Firm 2

Firm 1		*D*	*ND*
	D	Π_1^D , Π_2^D	Π_1^{1D}, Π_2^{1D}
	ND	Π_1^{2D}, Π_2^{2D}	Π_1^{ND}, Π_2^{ND}

Figure 1. The Strategic Interaction between the Quantity-Setting Firms in the First Stage

Firm 2

Firm 1		D	ND
	D	Ψ_1^D, Ψ_2^D	Ψ_1^{1D}, Ψ_2^{1D}
	ND	Ψ_1^{2D}, Ψ_2^{2D}	Ψ_1^{ND}, Ψ_2^{ND}

Figure 2. The Strategic Interaction between the Price-Setting Firms in the First Stage