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ABSTRACT

The Effects of Disclosure Regulation on Innovative Firms: Private Values*

by Jos Jansen

Firms in an R&D race actively manage rivals' beliefs by disclosing and concealing information on their cost of investment. The firms' disclosure strategies affect their incentives to invest in R&D, and to acquire information. We compare equilibria under voluntary disclosure with those under mandatory disclosure in a model where the firms' cost of investment are identically independently distributed. Under voluntary disclosure firms conceal bad news, and disclose good news only if little knowledge spills over to their rival. Under mandatory disclosure firms expect higher profits for given information acquisition investments, but they may acquire less information.

Keywords: R&D competition, disclosure regulation, knowledge spillovers

JEL Classification: D82, D83, L23, O31, O32

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ZUSAMMENFASSUNG

Die Wirkung von Offenlegungsvorschriften auf innovative Firmen: Unkorrelierte Werte

Unternehmen, welche an einem F&E -Wettbewerb teilnehmen, managen aktiv die Erwartungen ihrer Konkurrenten, in dem sie gezielt entscheiden, ob sie Informationen über ihre Investitionskosten veröffentlichen oder geheim halten. Durch ihre Offenlegungsstrategien beeinflussen sie sowohl die Anreize Ihrer Konkurrenten Informationen zu sammeln, wie auch deren Anreize, F&E zu betreiben. Anhand eines Modells, in dem die Investitionskosten der Unternehmen unabhängig verteilt sind, vergleicht der Beitrag Gleichgewichte in denen die Unternehmen freiwillig wählen, ob sie ihre Informationen offen legen wollen, mit den Gleichgewichten, bei denen Unternehmen ihre Information offen legen müssen. Können die Unternehmen selbstständig entscheiden, ob sie ihre Informationen offen legen wollen, so führt dies dazu, dass sie schlechte Nachrichten verbergen und gute Nachrichten nur dann veröffentlichen, wenn wenig ihres Wissens von den Konkurrenten genutzt werden kann. Sind die Unternehmen jedoch verpflichtet ihre Informationen offenzulegen, so erwarten sie einerseits höhere Profite für gegebene Informationsinvestitionen, aber investieren andererseits u.U. weniger in die Informationsbeschaffung.

1 Introduction

A basic property of research and development (R&D) is that it generates information for the firms that invest in it. Usually this information is private to the firms and is actively acquired by them. This paper, and companion paper Jansen (2001), discusses how information about the firms' cost of R&D investment affects R&D competition and how these anticipated effects determine the firms' incentives to strategically disclose information.

In many innovative industries firms strategically preannounce their innovations. For example, in the operating system market it is often claimed that Microsoft (MS) is using preannouncements of its operating system upgrades to drive competition out of their market.[1] Such a preannouncement strategy is called a "vaporware" strategy. Disclosing good news about your own capabilities of introducing a new product in the market, discourages rivals to invest in the development of competing products. Taking a lead in the race gives the leading firm a strategic advantage, which discourages its rival to invest, e.g. see Grossman and Shapiro (1987), and Harris and Vickers (1987). This is a "strategic effect".

The strategic effect can be observed in another case. British Biotech (BB) is a pharmaceutical firm whose main activity is research on and development of anti-cancer drugs. In the Spring of 1998 director of clinical research Andrew Millar of BB was sacked after disclosing bad news about BB's research and commercial strategy. As a result of the disclosure BB's stock market value collapsed, reflecting its reduced opportunities in the race for anti-cancer drugs. By concealing their bad test results, the firm tried to keep the market optimistic about its capabilities of introducing a new drug shortly.[2] Both cases suggest the predominance of the strategic effect of information disclosure. Disclosing good news, and concealing bad news about yourself makes your rivals believe that you will be a strong competitor in the remainder of the race.

Although the disclosure strategies are driven by the same strategic effect, regulatory responses differed substantially. In the 1994-95 licencing court case against Microsoft Corp., MS's vaporware practices where investigated (e.g. see US vs MS 27/01/1995). This did not lead to any restrictive regulation of MS's announcements.

[1]See e.g. Lopatka and Page (1995), Prentice (1996), Shapiro (1996), United States v. Microsoft, Civil Action No. 94-1564, and Shapiro and Varian (1999). An extensive anacdotical report on Microsoft's strategies is presented in Wallace and Erickson (1992).

[2]For coverage on this case, e.g. see *Financial Times* April 21, 27, and their survey at May 2/3 1998.

Regulations in the pharmaceutical industry, however, require firms to disclose their intermediate testing results. The attempted concealment by BB had severe negative consequences for its chances to get approval from the European Medical Evaluation Agency (EMEA) to sell developed drugs. In this paper we study the effects of disclosure regulation on firms' R&D strategies and profits. In particular, we compare firms' investments and profits under a regime of mandatory disclosure with those under voluntary disclosure.

A firm's preannouncement need not only have a strategic effect on the expectations in the industry, but can also reveal some valuable information about the innovation's content to the industry. When knowledge about the contents of the innovation spills over to rival firms after a preannouncement, this enables rival firms to catch up in the R&D race, which lowers a firm's incentive to preannounce its innovation. This informational catching-up effect is central in most patent design literature (e.g. see Scotchmer, 1991). Therefore a preannouncing firm faces the following trade-off. On the one hand the firm creates a strategic advantage by revealing it is a strong R&D competitor. On the other hand the disadvantage of a preannouncement is that some of the contents of the innovation spills over to the industry, which makes rival firms catch up in the R&D race. While the strategic effect gives firms an incentive to preannounce innovations, the informational catching-up effect encourages concealment of information. This paper illustrates the effect of this trade-off on the firms' strategic disclosure decisions, and on their incentives to invest in R&D.

In the companion paper, i.e. Jansen (2001), the strategic effect of information disclosure is countervailed by a different informational effect. The companion paper studies industries in which one firm's intermediate success gives not only an indication of this firm's capabilities of developing the new product, but also of that of its rivals. That is, firms' R&D costs are correlated. After an early intermediate success by one firm, rivals become more optimistic about their opportunities, and increase their investments to obtain the innovation first. But when favorable information for one firm also encourages rivals, the firm has an incentive to prevent its rivals from learning this information. Such an informational effect induces firms to conceal good news about their R&D cost, and disclose only bad news. Jansen (2001) studies the consequences of the trade-off between this informational effect and the strategic effect for investments and profits.

Finally we make a first step in endogenizing the amount of information that firms have by introducing strategic information acquisition investments in the model.

Related literature: Contests in which firms learn after investing are studied by e.g. Hendricks and Kovenock (1989), and Choi (1991). These papers assume that information flows freely between competing firms. We show in this paper whether full information disclosure is compatible with the firms incentives, and whether it is desirable for firms.

Recent papers, such as Katsoulacos and Ulph (1998), Gosálbez and Díez (2000), and Rosenkranz (2001), study information disclosure incentives in research joint ventures. Although these studies provide valuable insights in the incentives for information disclosure by innovative firms, they focus on the effects of cooperation between firms. We study the incentives to disclose information in a competitive setting, and focus on the effects of disclosure regulation.

"Vaporware", i.e. strategic preannouncement of good news and concealment of bad news, has been analyzed in some papers. One of the first papers to point to the potential strategic implications of preannouncements is Ordover and Willig (1981). In a seminal contribution by Farrell and Saloner (1986) the strategic effects of product preannouncements are mainly driven by consumers' myopia: consumers only anticipate a new product after the preannouncement of it. Both Levy (1997), and Lopatka and Page (1995) note that in a signalling setting preannouncements only have strategic effects when false announcements affect rival's or consumers' beliefs. Haan (2000) provides a signalling model of vaporware with intelligent consumers. False preannouncements do not affect consumers' beliefs and no information is revealed in equilibrium. Our paper assumes partially verifiability of information, and therefore does not obtain cheap talk equilibria. A recent paper by Gerlach (2000) studies the effects of preannouncements on industry entry, and social welfare. The paper differs in at least two respects from ours. First it studies an asymmetric competitive setting in which a potential entrant tries to gain future consumers' demand by preannouncing a new product. Our paper studies a setting in which two firms compete in all stages of the race. Second, Gerlach's policy analysis differs from ours, since it compares mandatory disclosure with full concealment. Although this is an interesting theoretical exercise, in practice preannouncements are hard to forbid, since the information is most valuable for producers of complementary products (such as hardware and applications software producers). Our paper compares mandatory and voluntary disclosure. Some empirical support for the emergence of vaporware effects in the Digital Versatile Disc (DVD) player industry is given in Dranove and Gandal (2001). In our paper we present the first model that I know of that results in strategic preannouncements among competing innovative firms.

A powerful result in the theory of strategic disclosure of verifiable information is the "unraveling result". Seminal contributions by Grossman (1981), Milgrom (1981), Milgrom and Roberts (1986), and Okuno-Fujiwara *et al.* (1990) study this result. When it is known that the sender of information is informed, and information is costlessly verifiable, he cannot do better than disclose his information, given skeptical equilibrium beliefs of the receiver. This result relies on the assumptions that information is costlessly verifiable and that it is known that the sender is informed. Uncertainty about whether or not the sender is informed and non-verifiability of uninformedness disables the unraveling result in most cases. Austen-Smith (1994) shows that when the receiver is uncertain about the informedness of the sender, the sender can conceal some of his information in equilibrium. In equilibrium good news is disclosed while bad news is concealed from the receiver. This argument is generalized and refined by Shin (1994). Recently Krishnan *et al.* (1996) provide empirical evidence that firms partially disclose earnings information to the financial market. We will use a similar framework of uncertain informedness to study strategic disclosure by racing R&D laboratories.

The incentives to acquire and disclose information have been studied in firm-financial market (see Verecchia, 1990), buyer-seller (see Shavell, 1994) and lobbyist-government (see Lagerlöf, 1997) settings. These papers endogenize the degree of informedness of the sender, but abstract from competition between senders. Papers in which firms strategically disclose information under competition are Admati and Pfleiderer (2000), Dewatripont and Tirole (1999), and Shin (1998). The setup of these papers, however, is such that senders disclose or conceal information to a third party. Both Shavell (1994) and Admati and Pfleiderer (2000) are interested in the effects of disclosure regulation. This is a main theme of this paper too.

Our contribution to the existing literature is twofold. First we study a problem in which competing firms disclose to each other. Disclosed information affects competition in R&D. And second we endogenize the extent to which firms are uninformed, by allowing firms to acquire costly information. This means that we endogenize the costs and benefits of both information acquisition and disclosure. This is the main contribution of this paper.

The paper is organized as follows. In the next section of this paper we describe the model. The third section discusses the benchmark of joint-profit-maximizing investments. Section 4 gives equilibrium R&D investments and profits when firms are required to disclose their information. We compare the benchmark investments with the equilibrium investments under mandatory disclosure. Section 5 gives the equilibrium R&D investments and disclosure choices when firms voluntarily disclose information, and we compare expected profits under mandated disclosure with those under voluntary disclosure. After this basic analysis we introduce knowledge spillovers in the sixth section. In section 7 we endogenize the firms' informedness by introducing information acquisition investments. Finally section 8 concludes the paper. All proofs to the paper's main propositions are relegated to the Appendix.

2 The Model

Two firms compete for an innovation. At the beginning of the race each firm does not know its cost of investment, θ_i for firm i, with $i = 1, 2$. Firm i has either low costs of investment, $\theta_i = \underline{\theta}$, or high costs of investment, $\theta_i = \overline{\theta}$, with $0 < \underline{\theta} < \overline{\theta}$ and $i = 1, 2$. The two firms' costs are identically independently distributed. The prior probability for firm i to have low R&D cost is p, with $0 < p < 1$.

Firm i learns about its cost of investment from a signal, Θ_i. With probability r_i firm i learns its true cost of investment, $\Theta_i = \theta_i$. However, with probability $1 - r_i$ firm i receives an uninformative signal, $\Theta_i = \varnothing$. Firm i's information from nature is summarized in figure 1.

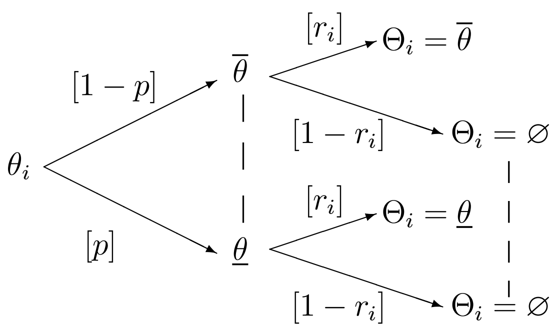

Figure 1: Firm i's information

Information obtained by firms is verifiable. Only the fact whether or not a firm is informed is not verifiable. If firm i receives information θ_i, it can choose to either disclose or conceal this, i.e. the firm chooses its communication $\delta_i(\theta_i)$ from the set $\{\theta_i, \varnothing\}$. An uninformed firm can only state $\delta_i(\varnothing) = \varnothing$. It therefore suffices to denote firm i's disclosure rule as $(\delta_i(\underline{\theta}), \delta_i(\overline{\theta}))$. We denote the realization of rule $\delta_i(.)$ as δ_i^*, with $\delta_i^* \in \{\delta_i(\Theta_i)|\Theta_i \in \{\underline{\theta}, \overline{\theta}, \varnothing\}\}$, i.e. δ_i^* is the message from firm i to j, for $i, j = 1, 2$ and $i \neq j$.

After signals are received from nature and rivals, each firm invests in R&D by investing $D_i \in [0, 1]$, at cost $C(D_i; \theta_i) = \frac{1}{2}\theta_i D_i^2$ with $i = 1, 2$. Note that firm i's cost of investment is increasing in θ_i. With probability D_i firm i invents, with probability $1 - D_i$ it does not invent. In this paper we study a "winner-takes-all" race. A firm gets payoff W, if it is the only firm that invents. If both firms invent, both firms get payoff T. If a firm does not invent, it gets no payoff. Naturally, we take $W \geq 2T \geq 0$. Define $\Delta \equiv W - T$ as the prize difference between winning and tying in the race. Because T is non-negative and cannot exceed $\frac{1}{2}W$, we obtain that $\frac{1}{2}W \leq \Delta \leq W$. For convenience we assume that $\underline{\theta} \geq 3\Delta$, which enables us to focus on interior R&D investment solutions.

Firms are risk-neutral. Given the cost of investment θ_i, firm i's expected R&D profit is:

$$\begin{aligned} \pi_i(\mathbf{D}; \theta_i) &= D_i(1 - D_j)W + D_i D_j T - \frac{1}{2}\theta_i D_i^2 \\ &= D_i(W - D_j\Delta) - \frac{1}{2}\theta_i D_i^2, \end{aligned} \tag{2.1}$$

with $\mathbf{D} = (D_i, D_j)$. We solve the game backwards, and restrict the analysis to symmetric, pure strategy equilibria.

3 Benchmark: Joint-Profit-Maximization

In this section we solve for the joint-profit-maximizing outcome of the race. Note that for joint profits full disclosure is never worse than any other disclosure rule — firms can always choose to ignore disclosed information. It is therefore optimal to take $\delta_i(\Theta_i) \equiv \Theta_i$ for $i = 1, 2$. Firm i's expected investment cost, θ_i^E, depends as follows on its signal:

$$\theta^E(\Theta_i) = \begin{cases} \underline{\theta}, \text{ for } \Theta_i = \underline{\theta} \\ E(\theta), \text{ for } \Theta_i = \varnothing \\ \overline{\theta}, \text{ for } \Theta_i = \overline{\theta}. \end{cases} \tag{3.1}$$

Total expected R&D profit, given signals (Θ_i, Θ_j), is:

$$E_\theta \left\{ \sum_{\ell=1}^{2} \pi_\ell(D; \theta_\ell) \middle| \Theta_i, \Theta_j \right\} = W \sum_{\ell=1}^{2} D_\ell - 2\Delta D_i D_j - \frac{1}{2} \sum_{\ell=1}^{2} \theta^E(\Theta_\ell) D_\ell^2. \tag{3.2}$$

This gives the following joint-profit-maximizing R&D investment $\overline{D}_i$ for firm i:

$$\theta^E(\Theta_i)\overline{D}_i = W - 2\Delta\overline{D}_j, \text{ or} \tag{3.3}$$

$$\overline{D}_i(\Theta_i, \Theta_j) = \frac{W\left(\theta^E(\Theta_j) - 2\Delta\right)}{\theta^E(\Theta_i)\theta^E(\Theta_j) - 4\Delta^2}, \text{ with } i, j = 1, 2,\ i \neq j. \tag{3.4}$$

Note that it is best to let a more efficient firm i, $\theta^E(\Theta_i) < \theta^E(\Theta_j)$, invest relatively more in R&D. Firm i's joint-profit-maximizing investments decrease in its expected costs, $\theta^E(\Theta_i)$, for any given expected rival's costs $\theta^E(\Theta_j)$. And a firm's investment increases in its rival's expected cost of investment, given its own expected costs. Firm i's maximum expected R&D profit is as follows:

$$\overline{\pi}_i(\Theta_i, \Theta_j) \equiv E_\theta\left(\pi_i(\overline{\mathbf{D}}; \theta_i)\,|\Theta_i, \Theta_j\right) = \frac{1}{2}W\overline{D}_i(\Theta_i, \Theta_j), \text{ for } i = 1, 2. \tag{3.5}$$

The intuitive result that firms' investments and profits depend on their relative costs of investment is in contrast with results in companion paper Jansen (2001). Since in that paper the costs of investment are identical, due to perfect correlation, only the absolute cost of investment matters.

4 Mandatory Disclosure

In this section we study the equilibrium in which firms are required to disclose their information (Θ_i, Θ_j). Such a disclosure regulation could be implemented by the threat of severe penalties after withholding of information is discovered. Such a regulation is effectively chosen by the European Medical Evaluation Agency for evaluating medicine innovations, as argued in the introduction. Observe that the only difference between the benchmark and this case is that we introduce competition in R&D.

When firms are required to disclose their signals, they base their investment decision on their relative costs of investment. Firm i's expected profits given firms' signals Θ is:

$$E_\theta\left(\pi_i(\mathbf{D}; \theta_i)\,|\Theta_i, \Theta_j\right) = (W - \Delta D_j)D_i - \frac{1}{2}\theta^E(\Theta_i)D_i^2. \tag{4.1}$$

Profit maximization gives the following equilibrium investment and profit:

$$\widehat{D}_i(\Theta_i, \Theta_j) = \frac{W\left(\theta^E(\Theta_j) - \Delta\right)}{\theta^E(\Theta_i)\theta^E(\Theta_j) - \Delta^2} \text{ and} \tag{4.2}$$

$$\widehat{\pi}_i(\Theta_i, \Theta_j) \equiv E_\theta\left(\pi_i(\widehat{\mathbf{D}}; \theta_i)\,|\Theta_i, \Theta_j\right) = \frac{1}{2}\theta^E(\Theta_i)\widehat{D}_i(\Theta_i, \Theta_j)^2, \tag{4.3}$$

respectively, with $i, j = 1, 2$, $i \neq j$. Firm i's equilibrium investments depend on expected costs $\theta^E(\Theta_i)$ and $\theta^E(\Theta_j)$ in a similar fashion as its joint-profit-maximizing investments do. Competing firms do not internalize the adverse effect that an increase in one firm's investment has on the chance of its rival to win the race. This business-stealing effect causes firms to overinvest in R&D, which is shown in the following lemma, for $i = 1, 2$ and $i \neq j$.

Lemma 1 *In the race with mandatory information disclosure both firms overinvest in R&D:* $\widehat{D}_i(\Theta_i, \Theta_j) > \overline{D}_i(\Theta_i, \Theta_j)$ *for all* (Θ_i, Θ_j).

5 Voluntary Disclosure

In the previous sections firms were required to disclose their information. In this section we characterize firms' equilibrium R&D investments after firms disclose only good news about their R&D cost, i.e. $(\delta_i(\underline{\theta}), \delta_i(\overline{\theta})) = (\underline{\theta}, \varnothing)$. A firm that discloses good news and conceals bad news about its cost of investment discourages its rival to invest in R&D. Disclosure of only low costs makes a firm's rival expect strong competition of the disclosing firms. We call such a disclosure choice vaporware disclosure, and we show that firms actually choose this disclosure rule in equilibrium.

5.1 Equilibrium Investments

We derive the R&D investments under the vaporware disclosure rule, $(\delta_i(\underline{\theta}), \delta_i(\overline{\theta})) = (\underline{\theta}, \varnothing)$ for $i = 1, 2$. Firms' incentives to invest under vaporware are driven by the strategic effect of information disclosure. First we introduce the following notation: firm i that received signal Θ_i, consequently sends message $\delta_i^* = \delta_i(\Theta_i)$, and received message δ_j^* invests $\widetilde{D}_i(\Theta_i; \delta_i^*, \delta_j^*)$ in equilibrium. We distinguish three different situations for firms. Either both firms disclose, only one firm discloses, or both firms conceal information. We discuss firms' equilibrium investments in these situations below.

When both firms learn that they have low costs of investment, they disclose this cost information. They therefore invest as under mandatory disclosure, i.e. $\widetilde{D}_i(\underline{\theta}; \underline{\theta}, \underline{\theta}) = \widehat{D}_i(\underline{\theta}, \underline{\theta})$.

The second case is one in which firm i discloses low costs, while firm j discloses no information: $(\delta_i^*, \delta_j^*) = (\underline{\theta}, \varnothing)$. In that case firm j could either be a high-cost firm, or an uninformed firm. Given vaporware disclosure, firm i assigns probability q_j to facing an informed firm j, with

$$q_j \equiv \frac{r_j(1-p)}{1-r_jp} \tag{5.1}$$

and maximizes its expected profits. This gives firm i's first-order condition:

$$\underline{\theta} D_i = W - \Delta\left[q_j D_j(\overline{\theta}) + (1-q_j)D_j(\varnothing)\right]. \tag{5.2}$$

Firm j has complete information about its rival's costs, and its investments are determined by the following first-order conditions:

$$E(\theta)D_j(\varnothing) = W - \Delta D_i \text{ and } \overline{\theta}D_j(\overline{\theta}) = W - \Delta D_i. \tag{5.3}$$

Note that $E(\theta)D_j(\varnothing) = \overline{\theta}D_j(\overline{\theta})$. When we substitute this in firm i's first-order condition, and define β_j as:

$$\beta_j \equiv q_j E(\theta) + (1-q_j)\overline{\theta}, \tag{5.4}$$

we easily derive the following equilibrium R&D investments:

$$\widetilde{D}_i(\underline{\theta};\underline{\theta},\varnothing) = \frac{\left(E(\theta)\overline{\theta} - \beta_j\Delta\right)W}{\underline{\theta}E(\theta)\overline{\theta} - \beta_j\Delta^2}, \text{ and} \tag{5.5}$$

$$\widetilde{D}_j(\Theta_j;\varnothing,\underline{\theta}) = \frac{\overline{\theta}E(\theta)(\underline{\theta}-\Delta)W}{\theta^E(\Theta_j)\left(\underline{\theta}E(\theta)\overline{\theta} - \beta_j\Delta^2\right)}, \text{ for } \Theta_j \in \{\overline{\theta},\varnothing\}. \tag{5.6}$$

Note that firm j invests less if it received bad news, and firm j always invests less than firm i in this equilibrium. After information $(\underline{\theta},\varnothing)$ is disclosed, firms know that firm i has lower expected marginal costs of investment than firm j. This encourages firm i, and discourages firm j to invest in R&D.

Since β_j is decreasing in r_j, it is easily verified that $\widetilde{D}_i(\underline{\theta};\underline{\theta},\varnothing)$ is increasing in r_j, while both $\widetilde{D}_j(\varnothing;\varnothing,\underline{\theta})$ and $\widetilde{D}_j(\overline{\theta};\varnothing,\underline{\theta})$ are decreasing in r_j. When firm j's signal precision r_j increases and firm j sends an uninformative signal, firm i puts more weight on competing with a high-cost firm j. This encourages firm i, and discourages firm j in the R&D stage of the race. In particular, when firm j is expected to be uninformed, $r_j = 0$, firms invest their full disclosure amounts $\widehat{D}_i(\underline{\theta},\varnothing)$ and $\widehat{D}_j(\varnothing,\underline{\theta})$, respectively. If firm j is expected to be fully informed, $r_j = 1$, firms invest in equilibrium $\widehat{D}_i(\underline{\theta},\overline{\theta})$ and $\widehat{D}_j(\overline{\theta},\underline{\theta})$, respectively. For signal precisions strictly between zero and one, firm i invests strictly between these mandated disclosure investment levels: $\widehat{D}_i(\underline{\theta},\varnothing) < \widetilde{D}_i(\underline{\theta};\underline{\theta},\varnothing) < \widehat{D}_i(\underline{\theta},\overline{\theta})$ for $0 < r_j < 1$. For $0 < r_j < 1$, informed firm j invests more under vaporware disclosure, $\widetilde{D}_j(\overline{\theta};\varnothing,\underline{\theta}) > \widehat{D}_j(\overline{\theta},\underline{\theta})$, while uninformed firm j invests less, $\widetilde{D}_j(\varnothing;\varnothing,\underline{\theta}) < \widehat{D}_j(\varnothing,\underline{\theta})$. Under vaporware disclosure informed firm j pools with its uninformed counterpart, which discourages firm i's investments, and consequently encourages firm j to invest. When firm j is actually uninformed and pools with its high cost counterpart, this encourages its rival and discourages firm j to invest in R&D.

Finally we consider the case in which both firms disclose no information: $(\delta_i^*,\delta_j^*) = (\varnothing,\varnothing)$. This gives the following first-order conditions (for $\Theta_i \in \{\overline{\theta},\varnothing\}$ and $i,j = 1,2$, with $i \neq j$):

$$\theta^E(\Theta_i)D_i(\Theta_i) = W - \Delta\left[q_j D_j(\overline{\theta}) + (1-q_j)D_j(\varnothing)\right]. \tag{5.7}$$

Again, this gives $E(\theta)D_j(\varnothing) = \overline{\theta}D_j(\overline{\theta})$, and equilibrium investments:

$$\widetilde{D}_i(\Theta_i;\varnothing,\varnothing) = \frac{E(\theta)\overline{\theta}\left(E(\theta)\overline{\theta} - \beta_j\Delta\right)W}{\theta^E(\Theta_i)\left(E(\theta)^2\overline{\theta}^2 - \beta_i\beta_j\Delta^2\right)}, \text{ for } \Theta_i \in \{\overline{\theta},\varnothing\}. \tag{5.8}$$

for $i = 1,2$, and $i \neq j$. Note that $\widetilde{D}_i(\overline{\theta};\varnothing,\varnothing) < \widetilde{D}_i(\varnothing;\varnothing,\varnothing)$. An uninformed firm is more optimistic about its costs, and therefore invests more in equilibrium.

When firm j's signal precision r_j increases, it becomes more likely that concealing firm j actually received bad news. This encourages firm i to invest in R&D. Therefore firm i's investments are increasing in r_j. Conversely firm j's R&D investments decrease in response to firm i's increased investments. If firms are equally likely to be informed, i.e. $r_i = r$ for $i = 1,2$, and likelihood r increases, the direct positive effect dominates the negative effect, and consequently investments increase. It is intuitive that: $\widehat{D}_i(\Theta_i,\varnothing) \leq \widetilde{D}_i(\Theta_i;\varnothing,\varnothing) \leq \widehat{D}_i(\Theta_i,\overline{\theta})$ for $\Theta_i \in \{\varnothing,\overline{\theta}\}$, with $\widetilde{D}_i(\varnothing;\varnothing,\varnothing) = \widehat{D}_i(\varnothing,\varnothing)$ for $r_i = r_j = 0$, and $\widetilde{D}_i(\overline{\theta};\varnothing,\varnothing) = \widehat{D}_i(\overline{\theta},\overline{\theta})$ for $r_i = r_j = 1$.

Firm i's expected equilibrium R&D profits, given disclosed information $(\delta_i(\Theta_i),\delta_j^*)$ and equilibrium beliefs, are:

$$\widetilde{\pi}_i(\Theta_i;\delta_i(\Theta_i),\delta_j^*) = \frac{1}{2}\theta^E(\Theta_i)\widetilde{D}_i(\Theta_i;\delta_i(\Theta_i),\delta_j^*)^2, \tag{5.9}$$

for $i,j = 1,2$ and $i \neq j$.

We summarize the findings of this subsection in the following lemma:

Lemma 2 *Take* $(\delta_i(\underline{\theta}),\delta_i(\overline{\theta})) = (\underline{\theta},\varnothing)$, $r_i = r_j = r$ *and* $i = 1,2$, $i \neq j$.
(i) For $0 < r < 1$, *equilibrium R&D investments have the following properties:*
(i.a) $\widetilde{D}_i(\overline{\theta};\varnothing,\underline{\theta}) < \widetilde{D}_i(\varnothing;\varnothing,\underline{\theta}) < \widetilde{D}_i(\underline{\theta};\underline{\theta},\underline{\theta}) < \widetilde{D}_i(\underline{\theta};\underline{\theta},\varnothing)$, *and*
$\widetilde{D}_i(\overline{\theta};\varnothing,\underline{\theta}) < \widetilde{D}_i(\overline{\theta};\varnothing,\varnothing) < \widetilde{D}_i(\varnothing;\varnothing,\varnothing) < \widetilde{D}_i(\underline{\theta};\underline{\theta},\varnothing)$;

(i.b) $\partial\widetilde{D}_i(\Theta_i;\delta_i(\Theta_i),\underline{\theta})/\partial r < 0$ *for* $\Theta_i \in \{\varnothing,\overline{\theta}\}$*, and*
$\partial\widetilde{D}_i(\Theta_i;\delta_i(\Theta_i),\varnothing)/\partial r > 0$ *for* $\Theta_i \in \{\underline{\theta},\varnothing,\overline{\theta}\}$;
(ii) R&D investments under mandatory and vaporware disclosure compare as follows:
(ii.a) $\widehat{D}_i(\Theta_i,\varnothing) \leq \widetilde{D}_i(\Theta_i;\widetilde{\delta}_i(\Theta_i),\varnothing) \leq \widehat{D}_i(\Theta_i,\overline{\theta})$, *for* $\Theta_i \in \{\underline{\theta},\varnothing,\overline{\theta}\}$,
$\widetilde{D}_i(\underline{\theta};\underline{\theta},\underline{\theta}) = \widehat{D}_i(\underline{\theta},\underline{\theta}), \widetilde{D}_i(\varnothing;\varnothing,\underline{\theta}) \leq \widehat{D}_i(\varnothing,\underline{\theta})$*, and* $\widetilde{D}_i(\overline{\theta};\varnothing,\underline{\theta}) \geq \widehat{D}_i(\overline{\theta},\underline{\theta})$;
(ii.b) For $r = 0$*:* $\widetilde{D}_i(\varnothing;\varnothing,\varnothing) = \widehat{D}_i(\varnothing,\varnothing)$
for $r = 1$*:* $\widetilde{D}_i(\Theta_i;\delta_i(\Theta_i),\delta_j(\Theta_j)) = \widehat{D}_i(\Theta_i,\Theta_j)$ *with* $\Theta_i,\Theta_j \in \{\underline{\theta},\overline{\theta}\}$,
$\widetilde{D}_i(\varnothing;\varnothing,\delta_j(\Theta_j)) = \frac{\overline{\theta}}{E(\theta)}\widehat{D}_i(\overline{\theta},\Theta_j)$ *with* $\Theta_j \in \{\underline{\theta},\overline{\theta}\}$.

5.2 Disclosure Equilibrium

In the previous subsection we characterized equilibrium R&D investments under the vaporware disclosure rule. This section shows that the vaporware rule is indeed chosen in equilibrium.

First we show that other pure-strategy disclosure rules are not chosen by both firms in equilibrium (see Appendix).

Lemma 3 *Under voluntary disclosure equilibria do not exist in which:*
(i) Both firms disclose all information: $(\delta_i(\underline{\theta}),\delta_i(\overline{\theta})) = (\underline{\theta},\overline{\theta})$*, for* $i = 1,2$*;*
(ii) Both firms conceal all information: $(\delta_i(\underline{\theta}),\delta_i(\overline{\theta})) = (\varnothing,\varnothing)$*, for* $i = 1,2$*;*

There is no equilibrium in which both firms completely disclose their information. If a firm's rival expects that all information is disclosed, the firm can discourage its rival to invest in R&D by unilaterally concealing high cost information. There is no equilibrium in which both firms fully conceal their information. An informed efficient firm creates a strategic advantage in the R&D stage of the race by unilaterally disclosing its cost of investment. Given these disclosure incentives it is intuitive that the following proposition holds.

Proposition 1 *In any symmetric pure-strategy equilibrium with voluntary disclosure firms disclose low cost information, while they conceal high costs:* $(\widetilde{\delta}_i(\underline{\theta}),\widetilde{\delta}_i(\overline{\theta})) = (\underline{\theta},\varnothing)$*, for* $i = 1,2$.

Note that the equilibrium disclosure rule is the opposite of the equilibrium rule for the model with perfect positive correlation between costs of investment, as in Jansen (2001). In that paper the strategic effect of information disclosure is generically dominated by an informational effect. With independently distributed costs of investment this informational effect of disclosure disappears, and results are completely driven by the strategic effect of disclosure. By preannouncing good news about your costs of investment, you disclose yourself as a tough competitor in the R&D stage of the game. This discourages your rival's investments. And since there is only one effect that drives this result, it holds for all parameter values.

5.3 Overall Profit Comparison

In this section we compare expected profits under mandatory disclosure with those under voluntary disclosure. Firm i's expected profit under mandatory disclosure is as follows:

$$\widehat{\Pi}_i(r_i, r_j) \equiv E_{\Theta_i}\left\{pr_j\widehat{\pi}_i(\Theta_i, \underline{\theta}) + (1 - pr_j)\left[q_j\widehat{\pi}_i(\Theta_i, \overline{\theta}) + (1 - q_j)\widehat{\pi}_i(\Theta_i, \varnothing)\right]\right\}. \quad (5.10)$$

Under mandatory disclosure firms evaluate the expected profit of disclosed costs. Conversely under vaporware disclosure firms evaluate the profit of expected costs. In particular firm i's expected profit under vaporware disclosure is as follows:

$$\widetilde{\Pi}_i(r_i, r_j) \equiv E_{\Theta_i}\left\{pr_j\widetilde{\pi}_i(\Theta_i; \widetilde{\delta}_i(\Theta_i), \underline{\theta}) + (1 - pr_j)\widetilde{\pi}_i(\Theta_i; \widetilde{\delta}_i(\Theta_i), \varnothing)\right\}. \quad (5.11)$$

Since the firms' profit functions are convex in their cost signals, they prefer the expected profit of disclosed signals over the profit of expected signals. We state this formally in the following proposition.

Proposition 2 *Firms that fully disclose their information expect higher profits than firms that choose vaporware disclosure strategies:* $\widehat{\Pi}_i(r_i, r_j) \geq \widetilde{\Pi}_i(r_i, r_j)$ *for all* (r_i, r_j).

Although firms have interim incentives to conceal bad news, *ex ante* they have an incentive to commit to full information disclosure. Disclosure regulation would help the firms to achieve higher *ex ante* expected profits.

6 Knowledge Spillovers

Not only information about the rival's costs of investment is relevant for a firm, but also the *contents* of the rival's R&D technology becomes valuable. When firm i discovers that it has low costs of investment while firm j has high costs, firm j would like to imitate its rival's R&D technology, and benefit from efficient R&D technology. To model this effect we assume that an exogenous fraction $\kappa \in [0, 1]$ of an efficient firm's knowledge spills over to the rival after disclosure. When a firm's rival discloses low costs, the firm can benefit from the knowledge spillover. Naturally, whenever firm i does not disclose a low cost signal, no knowledge spills over to firm j. Firm i's expected R&D cost after observing signals (Θ_i, δ_j^*) is therefore:

$$\theta^\kappa(\Theta_i, \delta_j^*) = \begin{cases} \kappa\underline{\theta} + (1-\kappa)\theta^E(\Theta_i), \text{ for } \delta_j^* = \underline{\theta}, \\ \theta^E(\Theta_i), \text{ otherwise.} \end{cases} \tag{6.1}$$

Note that the case of no spillover, $\kappa = 0$, corresponds to the study of previous sections. The case of full spillover, $\kappa = 1$, under required disclosure effectively gives perfect positive correlation with $\Pr[\theta_i = \theta_j = \underline{\theta}] = 1-(1-p)^2$, and $\Pr[\theta_i = \theta_j = \overline{\theta}] = (1-p)^2$.

In companion paper Jansen (2001), where R&D costs are perfectly positively correlated, knowledge spillovers are not relevant. Since firms have identical costs of investment, information disclosure does not enable firms to catch up.

6.1 R&D Investments with Knowledge Spillovers

First we study the effects that knowledge spillovers have on the R&D investment strategies of the previous sections. That is, we take the disclosure rules of previous sections as given, and focus on R&D. In the next subsection we find conditions under which these disclosure strategies are still employed in equilibrium, and what other disclosure equilibrium may emerge.

The joint-profit-maximizing outcome and the equilibrium investments under mandatory disclosure are similar to those without knowledge spillovers, with $\theta^E(\Theta_i)$ and $\theta^E(\Theta_j)$ replaced by $\theta^\kappa(\Theta_i, \Theta_j)$ and $\theta^\kappa(\Theta_j, \Theta_i)$, respectively.

The equilibrium R&D investments under vaporware disclosure only differ from those in the previous section after firms send message combination $(\delta_i^*, \delta_j^*) = (\underline{\theta}, \varnothing)$. In that case the equilibrium investments $\widetilde{D}_i^\kappa(\underline{\theta}; \underline{\theta}, \varnothing)$ and $\widetilde{D}_j^\kappa(\Theta_j; \varnothing, \underline{\theta})$ are as in expressions (5.5) and (5.6), with $E(\theta)$, $\overline{\theta}$, and β_j replaced by $\theta^\kappa(\varnothing, \underline{\theta})$, $\theta^\kappa(\overline{\theta}, \underline{\theta})$, and β_j^κ, respectively, where $\beta_j^\kappa \equiv \kappa\underline{\theta} + (1-\kappa)\beta_j$.

The more knowledge spills over from an efficient firm to its rival, the more aggressive the efficient firm's rival becomes, and therefore the lower its incentive to invest in R&D. The firm that receives the knowledge increases its R&D productivity, and has therefore a bigger incentive to invest in R&D. The more the receiving firm's productivity increases, the bigger this firm's investment incentives.

Given the effects of an increase in spillover on the R&D investments, we can study the overall effect of an increase in spillover on expected equilibrium profits. On the one hand, the more knowledge spills over to firm i from its rival, the higher firm

i's expected profit. It is therefore immediate that if firm i is always uninformed ($r_i = 0$), then its expected equilibrium profit increases in the knowledge spillover. On the other hand, if the amount of knowledge that spills over from firm i to its rival increases, this decreases firm i's expected profit. It is therefore immediate that if firm i's rival is uninformed ($r_j = 0$), i.e. information can only spill over from firm i to its rival, then firm i's expected equilibrium profit decreases in the knowledge spillover. For symmetric distributions of information among firms ($r_i = r_j$) the firms face a more subtle trade-off between these two opposing spillover effects. We show in the proposition below that in this case the positive effect on expected profits outweighs the negative effect.

Proposition 3 *(i) For $\Theta \neq (\underline{\theta}, \underline{\theta})$, and given disclosure rules of the previous sections, equilibrium investments of an efficient (resp. inefficient or uninformed) firm decrease (resp. increase) in the size of spillover κ:*
$\partial \widehat{D}_i^\kappa(\underline{\theta}, \Theta_j)/\partial\kappa < 0$ *and* $\partial \widetilde{D}_i^\kappa(\underline{\theta}; \underline{\theta}, \varnothing)/\partial\kappa < 0$ *for* $\Theta_j \in \{\overline{\theta}, \varnothing\}$, *and*
$\partial \widehat{D}_i^\kappa(\Theta_i, \underline{\theta})/\partial\kappa > 0$ *and* $\partial \widetilde{D}_i^\kappa(\Theta_i; \varnothing, \underline{\theta})/\partial\kappa > 0$, *for* $\Theta_i \in \{\overline{\theta}, \varnothing\}$.
(ii) If $r_i = r_j = r$, then expected equilibrium profits increase in knowledge spillover κ:
$\partial \widehat{\Pi}_i^\kappa(r, r)/\partial\kappa > 0$, *and* $\partial \widetilde{\Pi}_i^\kappa(r, r)/\partial\kappa > 0$.

It follows from part (ii) of the proposition that under mandatory disclosure firms expect to benefit if they commit *ex ante* to share information on the contents of their R&D technology. Under voluntary disclosure firms have similar incentives, provided that firms choose vaporware disclosure rules. However the firms' incentives to disclose low costs of investment decreases in the knowledge spillover. In the next subsection we study how equilibrium information disclosure rules depend on knowledge spillovers.

6.2 Disclosure with Knowledge Spillovers

The previous subsection took vaporware disclosure strategies as given. Now we study when firms do employ such strategies, and we find what other equilibrium may emerge.

Concerning the effect of knowledge spillovers on the firms' incentives to disclose information, we make two observations. First, an informed inefficient firm never has an incentive to disclose that it is inefficient. After the firm discloses bad news its rival only updates his beliefs on the disclosing firm, while his own cost expectation remains unchanged. Second, the disclosure incentives of an informed efficient firm depends on the size of the knowledge spillover κ. If only little knowledge spills over after disclosure, efficient firms disclose their low costs in equilibrium. The positive strategic effect of disclosure outweighs the negative spillover effect in this case. An informed efficient firm typically has an incentive to conceal its information, if too much knowledge spills over to its rival. For high enough κ the strategic effect of disclosure is outweighed by the spillover effect in most cases. Before we prove this in a proposition, we define the following parameter:

$$\alpha_i \equiv r_i p E(\theta)\overline{\theta} + r_i(1-p)\underline{\theta}E(\theta) + (1-r_i)\underline{\theta}\overline{\theta}, \tag{6.2}$$

and we introduce the following condition:

$$\alpha_i > \alpha_j - \left(E(\theta)\overline{\theta} - \alpha_j\right)\left(\underline{\theta}E(\theta)\overline{\theta} - \alpha_j \Delta\right)/\alpha_j \Delta. \tag{C.1}$$

Proposition 4 ***(i)*** *There is a critical spillover $\kappa^* \in (0,1)$ such that an equilibrium exists in which both firms preannounce iff $\kappa \leq \kappa^*$.*
(ii) *If for all $i, j = 1, 2$ $(i \neq j)$ condition C.1 holds, then there is a critical spillover $\kappa^o \in (0,1)$ such that an equilibrium exists in which both firms fully conceal iff $\kappa > \kappa^o$.*

Notice that condition C.1 is satisfied for both firms if firms receive information with equal probability, i.e. $r_i = r_j$. For sufficiently asymmetric precisions of information, one of the firms has an incentive to unilaterally disclose low R&D costs. In particular, if $r_i = \varepsilon$, $r_j = 1 - \varepsilon$, and $p = 1 - \varepsilon$ with $\varepsilon > 0$ sufficiently small, firm i may have an incentive to disclose its low R&D cost even if all knowledge spills over to its rival after disclosure ($\kappa = 1$). If r_j and p are high, firm i expects to face an informed rival with low R&D costs. Therefore the knowledge that spills over from firm i's disclosure of low cost is expected to have little effect on firm j's efficiency. But firm i's low-cost disclosure has a substantial effect on its rival's beliefs. If r_i is low, firm j expects that firm i is uninformed, and therefore (if $\overline{\theta} - \underline{\theta}$ is sufficiently big) a relatively weak R&D investor. By disclosing its cost of investment, firm i surprises its rival, and makes him realize that firm i will be an "aggressive" investor in the R&D stage of the game.

From propositions 3 (ii) and 4 we conclude that the expected profits under voluntary disclosure initially increase in the knowledge spillover (for $\kappa \leq \kappa^*$), and subsequently remains constant (for $\kappa > \kappa^o$). Under mandatory disclosure expected profits increase in the knowledge spillover for all κ.

7 Endogenous Information Acquisition

Disclosure regulation does not only affect the investment incentives after disclosure, but also has an impact on the incentives to acquire information. In this section we endogenize the firms' signal precisions (r_i, r_j). Firm i invests $R_i \in [0,1]$ at cost of investment $\frac{1}{2}\rho R_i^2$, where investment R_i is not observable and $\rho > 0$. Expected information acquisition investments are denoted as (r_i, r_j).

■ **Joint-Profit-Maximizing Investments:** In this subsection we determine the information acquisition investments that maximize total expected profits, given joint-profit-maximizing R&D investments. Firm i's expected profit, given joint-profit-maximizing R&D investments, is:

$$\begin{aligned}\overline{\Pi}_i(R_i, R_j) \;&=\; R_i \left\{ R_j E_{\theta_j}\left(E_{\theta_i}[\overline{\pi}_i(\theta_i,\theta_j)]\right) + (1-R_j)E_{\theta_i}[\overline{\pi}_i(\theta_i,\varnothing)]\right\} + \\ &\quad +(1-R_i)\left\{R_j E_{\theta_j}(\overline{\pi}_i(\varnothing,\theta_j)) + (1-R_j)\overline{\pi}_i(\varnothing,\varnothing)\right\}, \qquad (7.1)\end{aligned}$$

for $i, j = 1, 2$ and $i \neq j$. Define the industry's value of information given signal Θ_j as follows:

$$\overline{\Psi}(\Theta_j) \equiv E_{\theta_i}\left(\sum_{\ell=1}^{2}\overline{\pi}_\ell(\theta_i,\Theta_j)\right) - \sum_{\ell=1}^{2}\overline{\pi}_\ell(\varnothing,\Theta_j), \text{ for } \Theta_j \in \{\underline{\theta}, \overline{\theta}, \varnothing\}. \qquad (7.2)$$

It is easy to verify that $\sum_{\ell=1}^{2}\overline{\pi}_\ell(\Theta)$ is convex in $\theta^E(\Theta_i)$ for any $\theta^E(\Theta_j)$, and hence $\overline{\Psi}(\Theta_j) > 0$ for all Θ_j. Maximization of total expected profits, $\sum_{\ell=1}^{2}\left(\overline{\Pi}_\ell(\mathbf{R}) - \frac{\rho}{2}R_\ell^2\right)$, with respect to information acquisition investment R_i gives the following first-order condition:

$$\rho R_i = R_j E_{\theta_j}\left\{\overline{\Psi}(\theta_j)\right\} + (1-R_j)\overline{\Psi}(\varnothing). \qquad (7.3)$$

Since $\overline{\Psi}(\Theta_j) > 0$ for all Θ_j, the joint-profit-maximizing information acquisition investments are non-negative, $\overline{R}_i > 0$.

■ **Mandatory disclosure:** In the information acquisition stage each firm maximizes expected profits, given anticipated equilibrium R&D investments, $(\widehat{D}_i, \widehat{D}_j)$. Firm i's expected profit, given equilibrium R&D investments, $\widehat{\Pi}_i(R_i, R_j)$, is as $\overline{\Pi}_i(R_i, R_j)$ with $\overline{\pi}_i(\Theta)$ replaced by $\widehat{\pi}_i(\Theta)$. Define firm i's revenue of information acquisition given its rival's signal Θ_j as follows:

$$\widehat{\Psi}(\Theta_j) \equiv E_{\theta_i}\left\{\widehat{\pi}_i(\theta_i,\Theta_j)\right\} - \widehat{\pi}_i(\varnothing,\Theta_j). \qquad (7.4)$$

Since $\widehat{\pi}_i(\Theta)$ is convex in $\theta_i^E(\Theta)$, it is immediate that $\widehat{\Psi}(\Theta_j) > 0$ for all Θ_j. Maximizing $\widehat{\Pi}_i(R_i, R_j)$ towards R_i gives first-order condition:

$$\rho R_i = R_j E_{\theta_j}\left\{\widehat{\Psi}(\theta_j)\right\} + (1-R_j)\widehat{\Psi}(\varnothing), \qquad (7.5)$$

for $i, j = 1, 2$, $i \neq j$. It is immediate that $\widehat{R}_i > 0$, for $i = 1, 2$. In order to obtain an interior solution of this system of equations for R_i, we have to put a lower-bound on cost parameter ρ.

When we compare joint-profit-maximizing information acquisition investments with equilibrium investments under mandatory disclosure, we obtain that firms overinvest under mandatory disclosure.

Proposition 5 *Under full information disclosure firms overinvest in information acquisition, $\widehat{R}_i \geq \overline{R}_i$. This inequality is strict for interior equilibrium information acquisition investments.*

The proposition gives a result that is opposite to that under perfect positive correlation. As shown in Jansen (2001), firms with perfectly positively correlated costs of investment always underinvest in information acquisition. If the costs are identically independently distributed, firms can no longer free-ride on investments of their rival, and consequently their incentives to acquire information increase.

■ **Voluntary disclosure:** Before the firms choose their disclosure rules, they invest in information acquisition. We define firm i's expected value of information given disclosed information δ_j^* as follows:

$$\widetilde{\Psi}(\delta_j^*) \equiv E_{\theta_i}\left(\widetilde{\pi}_i(\theta_i; \widetilde{\delta}_i(\theta_i), \delta_j^*)\right) - \widetilde{\pi}_i(\varnothing; \varnothing, \delta_j^*), \text{ with } \delta_j^* \in \{\underline{\theta}, \varnothing\}. \tag{7.6}$$

Firm i's first-order condition of maximizing expected profit toward R_i is:

$$\rho R_i = pR_j \left\{\widetilde{\Psi}(\underline{\theta})\right\} + (1 - pR_j)\widetilde{\Psi}(\varnothing). \tag{7.7}$$

The information acquisition investment, $\widetilde{R}_i$, that results from these first-order conditions is the equilibrium investment. For the comparison between information acquisition investments under mandatory and vaporware disclosure, we need to compare the marginal revenues of information acquisition. We can rewrite the first-order condition of information acquisition under mandatory disclosure, expression (7.5), as follows:

$$\rho R_i = pR_j\widehat{\Psi}(\underline{\theta}) + (1 - pR_j)\left(Q_j\widehat{\Psi}(\overline{\theta}) + (1 - Q_j)\widehat{\Psi}(\varnothing)\right), \tag{7.8}$$

with $Q_j \equiv \frac{(1-p)R_j}{1-pR_j}$. A comparison of the terms in the right-hand-sides of expressions (7.7) and (7.8) gives the following. If firm j receives good news, $\Theta_j = \underline{\theta}$, then firm

i expects under voluntary disclosure relatively higher profit from being informed, and lower from remaining uninformed, i.e. $\widetilde{\Psi}(\underline{\theta}) > \widehat{\Psi}(\underline{\theta})$. This gives it a higher incentive to acquire information under vaporware disclosure. When firm j does not voluntarily disclose information, $\delta_j^* = \varnothing$, firm i faces the following trade-off. If firm i would acquire low or no cost information, $\Theta_i \in \{\underline{\theta}, \varnothing\}$, it would be better off under mandatory disclosure. The first observation gives the firm a lower incentive to acquire information, while the second gives the firm a higher incentive to acquire information under voluntary disclosure. If firm i would acquire bad news, $\Theta_i = \overline{\theta}$, its equilibrium R&D profit under voluntary disclosure would exceed the expected equilibrium profit under mandatory disclosure. This increases the firm's incentive to acquire information under voluntary disclosure. The relative disincentive of information acquisition under voluntary disclosure is outweighed by the two extra incentives, i.e. $\widetilde{\Psi}(\varnothing) > Q_j \widehat{\Psi}(\overline{\theta}) + (1 - Q_j)\widehat{\Psi}(\varnothing)$, if the difference between high and low cost is not too big. We prove this in the following proposition:

Proposition 6 *For any p, W, Δ and $\underline{\theta}$ there is an $\varepsilon > 0$, such that if $\overline{\theta} \leq \underline{\theta} + \varepsilon$, firms' equilibrium information acquisition investments under voluntary disclosure exceed those under mandatory disclosure, i.e. $\widetilde{R}_i \geq \widehat{R}_i$ for $i = 1, 2$. This holds with strict inequality for interior equilibrium information acquisition investments.*

■ **Overall Profit Comparison:** In the model with *endogenous* information acquisition investments the overall profit comparison should compare expected equilibrium profit $\widehat{\Pi}_i(\widehat{R}_i, \widehat{R}_j) - \frac{1}{2}\rho\widehat{R}_i^2$ with $\widetilde{\Pi}_i(\widetilde{R}_i, \widetilde{R}_j) - \frac{1}{2}\rho\widetilde{R}_i^2$. This profit comparison is not obvious for all parameter values. On the one hand, it follows from proposition 2 that for given (r_i, r_j) firms expect a higher equilibrium profit under mandatory disclosure than under voluntary disclosure. In particular, for $r_i = \widetilde{R}_i$ we obtain $\widehat{\Pi}_i(\widetilde{R}_i, \widetilde{R}_j) > \widetilde{\Pi}_i(\widetilde{R}_i, \widetilde{R}_j)$. On the other hand, proposition 6 establishes that in many cases firms acquire less information acquisition under mandatory disclosure than under voluntary disclosure, i.e. $\widehat{R}_i < \widetilde{R}_i$. Moreover, each firm's expected equilibrium profit under mandatory disclosure increases in the firms' information acquisition investments, i.e. $d\widehat{\Pi}_i(R, R)/dR > 0$ (see Appendix). Therefore $\widehat{\Pi}_i(\widehat{R}_i, \widehat{R}_j) < \widehat{\Pi}_i(\widetilde{R}_i, \widetilde{R}_j)$ for many parameter values. These two observations make the overall comparison between $\widehat{\Pi}_i(\widehat{R}_i, \widehat{R}_j)$ and $\widetilde{\Pi}_i(\widetilde{R}_i, \widetilde{R}_j)$ non-obvious in many cases. The choice for mandatory disclosure then depends on the trade-off between higher expected profits for given information acquisition investments, and lower incentives to acquire information. Observe that this trade-off is similar to that in companion paper Jansen (2001).

Naturally if there are parameter values that do not result in more information acquisition under voluntary disclosure, $\widehat{R}_i \geq \widetilde{R}_i$, then we immediately obtain that overall expected R&D profits are highest under mandatory disclosure, since: $\widehat{\Pi}_i(\widehat{R}_i, \widehat{R}_j) \geq \widehat{\Pi}_i(\widetilde{R}_i, \widetilde{R}_j) > \widetilde{\Pi}_i(\widetilde{R}_i, \widetilde{R}_j)$. In that case, provided that the costs of information acquisition do not differ greatly, firms would be better off under mandatory disclosure.

8 Conclusion

In this paper we developed a theory of information acquisition, strategic disclosure and R&D in a competitive setting. We have seen that disclosure regulation substantially affects firms' investments, both in information acquisition as well as in R&D. And finally, by comparing this paper's analysis with Jansen (2001), we have shown that correlation between the costs of R&D investment affect equilibrium disclosure and investments dramatically.

We have given a model in which vaporware emerges in equilibrium. We have seen that Microsoft's alleged strategic preannouncements, and British Biotech's attempted concealment can be explained in a dynamic, strategic setting of incomplete information. Furthermore we have been able to explain how firm's investments and profits are affected in the different regimes. In particular, firms expect higher profits for given information acquisition investments under mandatory disclosure, but they may acquire less information.

The paper assumes a "winner-take-all" race setting. It would be interesting to study the effects of introducing patents and licensing in this model. This could correct some of the equilibrium inefficiencies. A natural next step would be to study how results change for intermediate degrees of correlations. For intermediate degrees of correlation we would expect a more subtle trade-off between the informational and strategic effect of information disclosure. These extensions of the basic analysis await future research.

A Appendix

This Appendix contains proofs to the main propositions of this paper.

A.1 R&D Investments

The proofs of lemma 1 and 2 are straightforward.

A.2 Voluntary Disclosure

We prove lemma 3 and propositions 1 and 2, respectively.

A.2.1 Proof of Lemma 3

(i) Suppose full disclosure *is* chosen in equilibrium. Then firm j's R&D investments are $\widehat{D}_j(\Theta_j, \delta_i^*)$ for $\delta_i^*, \Theta_j \in \{\underline{\theta}, \overline{\theta}, \varnothing\}$. Given that firm j fully discloses its information Θ_j and holds beliefs consistent with full disclosure, an informed and inefficient firm i expects the following profit from disclosure:

$$\widehat{\pi}_i(\overline{\theta}, \Theta_j) = \frac{1}{2}\overline{\theta}\widehat{D}_i(\overline{\theta}, \Theta_j)^2 = \frac{1}{2}\overline{\theta}\left(\frac{\left(\theta^E(\Theta_j) - \Delta\right)W}{\overline{\theta}\theta^E(\Theta_j) - \Delta^2}\right)^2. \tag{A.1}$$

After firm i conceals $\overline{\theta}$ its rival invests $\widehat{D}_j(\Theta_j, \varnothing)$, and firm i's best response to this investment is as follows:

$$\overline{\theta}D_i = W - \widehat{D}_j(\Theta_j, \varnothing)\Delta \Leftrightarrow D_i = \frac{E(\theta)\left(\theta^E(\Theta_j) - \Delta\right)W}{\overline{\theta}\left(E(\theta)\theta^E(\Theta_j) - \Delta^2\right)}. \tag{A.2}$$

Concealment of high costs gives firm i an expected profit of $\frac{1}{2}\overline{\theta}D_i^2$. This profit exceeds the full disclosure profit, since for all $\Theta_j \in \{\underline{\theta}, \overline{\theta}, \varnothing\}$:

$$D_i = \frac{E(\theta)\left(\theta^E(\Theta_j) - \Delta\right)W}{\overline{\theta}E(\theta)\theta^E(\Theta_j) - \overline{\theta}\Delta^2} > \frac{E(\theta)\left(\theta^E(\Theta_j) - \Delta\right)W}{\overline{\theta}E(\theta)\theta^E(\Theta_j) - E(\theta)\Delta^2} = \widehat{D}_i(\overline{\theta}, \Theta_j), \tag{A.3}$$

(ii) Suppose full concealment *is* an equilibrium strategy for firms. Under full concealment the firms' equilibrium R&D investments $D^o(.)$ are determined by the following first-order conditions (for $\Theta_i \in \{\underline{\theta}, \overline{\theta}, \varnothing\}$):

$$\theta^E(\Theta_i)D_i^o(\Theta_i) = W - \left(r_j p D_j^o(\underline{\theta}) + r_j(1-p)D_j^o(\overline{\theta}) + (1-r_j)D_j^o(\varnothing)\right)\Delta. \tag{A.4}$$

This results in the following equilibrium R&D investments:

$$D_i^o(\Theta_i) = \frac{\underline{\theta} E(\theta)\overline{\theta}\left(\underline{\theta} E(\theta)\overline{\theta} - \alpha_j \Delta\right) W}{\theta^E(\Theta_i)\left(\underline{\theta}^2 E(\theta)^2 \overline{\theta}^2 - \alpha_i \alpha_j \Delta^2\right)}, \tag{A.5}$$

with α_i as defined in expression (6.2). Firm i's equilibrium profit under full concealment equals:

$$E_{\Theta_i}\left\{\pi_i^o(\Theta_i; \varnothing, \varnothing)\right\} = \frac{1}{2}\theta^E(\Theta_i) D_i^o(\Theta_i)^2. \tag{A.6}$$

Consider firm i's incentive to unilaterally disclose low R&D costs. After firm i's disclosure the firms' R&D investments are determined by the following first-order conditions:

$$\underline{\theta} D_i = W - \left(r_j p D_j(\underline{\theta}) + r_j(1-p) D_j(\overline{\theta}) + (1-r_j) D_j(\varnothing)\right)\Delta, \tag{A.7}$$

$$\text{and } \theta^E(\Theta_j) D_j(\Theta_j) = W - D_i \Delta, \text{ for } \Theta_j \in \{\underline{\theta}, \overline{\theta}, \varnothing\}. \tag{A.8}$$

which results in the following equilibrium R&D investment and profit for firm i:

$$D_i = \frac{\left(\underline{\theta} E(\theta)\overline{\theta} - \alpha_j \Delta\right) W}{\underline{\theta}^2 E(\theta)\overline{\theta} - \alpha_j \Delta^2}, \text{ and } \pi_i = \frac{1}{2}\underline{\theta} D_i^2, \text{ respectively.} \tag{A.9}$$

Clearly unilateral disclosure of low costs is profitable, since $D_i > D_i^o(\underline{\theta})$. This completes the proof.□

A.2.2 Proof of Proposition 1

Firm i's expected profits under vaporware disclosure are as follows:

$$E_{\delta_j^*}\left\{\widetilde{\pi}_i(\Theta_i; \widetilde{\delta}_i(\Theta_i), \delta_j^*)\right\} = p r_j \widetilde{\pi}_i(\Theta_i; \widetilde{\delta}_i(\Theta_i), \underline{\theta}) + (1 - p r_j)\widetilde{\pi}_i(\Theta_i; \widetilde{\delta}_i(\Theta_i), \varnothing), \tag{A.10}$$

for $\Theta_i \in \{\underline{\theta}, \overline{\theta}, \varnothing\}$ and $i = 1, 2$. Distinguish two unilateral deviations from the vaporware disclosure equilibrium.

First, consider firm i with $\Theta_i = \overline{\theta}$. If it unilaterally chooses to disclose its costs, it receives expected profits:

$$E_{\delta_j^*}\left\{\pi_i(\overline{\theta}; \overline{\theta}, \delta_j^*)\right\} = \frac{1}{2}\overline{\theta}\left(p r_j \widehat{D}_i(\overline{\theta}, \underline{\theta})^2 + (1 - p r_j) D_i^{\overline{\theta}}(\overline{\theta}; \overline{\theta}, \varnothing)^2\right), \tag{A.11}$$

where $D_i^{\overline{\theta}}(\overline{\theta}; \overline{\theta}, \varnothing)$ solves:

$$\overline{\theta} D_i = W - \Delta\left[q_j D_j(\overline{\theta}) + (1 - q_j) D_j(\varnothing)\right], \tag{A.12}$$

$$\theta^E(\Theta_j) D_j(\Theta_j) = W - \Delta D_i, \text{ for } \Theta_j \in \{\overline{\theta}, \varnothing\}, \tag{A.13}$$

and is therefore

$$D_i^{\overline{\theta}}(\overline{\theta};\overline{\theta},\varnothing)=\frac{\left(E(\theta)\overline{\theta}-\beta_j\Delta\right)W}{\left(E(\theta)\overline{\theta}^2-\beta_j\Delta^2\right)}. \tag{A.14}$$

It is straightforward to verify that $\widetilde{D}_i(\overline{\theta};\varnothing,\underline{\theta})>\widehat{D}_i(\overline{\theta},\underline{\theta})$ and $\widetilde{D}_i(\overline{\theta};\varnothing,\varnothing)>D_i^{\overline{\theta}}(\overline{\theta};\overline{\theta},\varnothing)$. And, therefore, $E_{\delta_j^*}\left\{\widetilde{\pi}_i(\overline{\theta};\varnothing,\delta_j^*)\right\}>E_{\delta_j^*}\left\{\pi_i(\overline{\theta};\overline{\theta},\delta_j^*)\right\}$.

Secondly, a $\underline{\theta}$-firm i should not have an incentive to conceal its costs. Expected profit from concealment is maximized for $\underline{\theta}D_i(\underline{\theta};\varnothing,\delta_j^*)=\overline{\theta}\widetilde{D}_i(\overline{\theta};\varnothing,\delta_j^*)$, with $\delta_j^*\in\{\underline{\theta},\varnothing\}$. This gives expected deviation profit of:

$$E_{\delta_j^*}\left\{\pi_i(\underline{\theta};\varnothing,\delta_j^*)\right\}=\frac{\overline{\theta}^2}{2\underline{\theta}}\left(pr_j\widetilde{D}_i(\overline{\theta};\varnothing,\underline{\theta})^2+(1-pr_j)\widetilde{D}_i(\overline{\theta};\varnothing,\varnothing)^2\right). \tag{A.15}$$

The deviation for $\underline{\theta}$-firm i is unprofitable because $\underline{\theta}\widetilde{D}_i(\underline{\theta};\underline{\theta},\underline{\theta})-\overline{\theta}\widetilde{D}_i(\overline{\theta};\varnothing,\underline{\theta})$ equals:

$$\frac{\left[\overline{\theta}\left(\underline{\theta}E(\theta)-(1-q_j)\Delta^2\right)-E(\theta)\left(\underline{\theta}^2-(1-q_j)\Delta^2\right)\right](\underline{\theta}-\Delta)W}{(\underline{\theta}-\Delta^2)\left(\underline{\theta}E(\theta)\overline{\theta}-\beta_j\Delta^2\right)}>0, \tag{A.16}$$

and $\underline{\theta}\widetilde{D}_i(\underline{\theta};\underline{\theta},\varnothing)-\overline{\theta}\widetilde{D}_i(\overline{\theta};\varnothing,\varnothing)$ equals:

$$\frac{\beta_j\Delta^2\left(E(\theta)\overline{\theta}-\beta_i\underline{\theta}\right)\left(E(\theta)\overline{\theta}-\beta_j\Delta\right)W}{\left(\underline{\theta}E(\theta)\overline{\theta}-\beta_j\Delta^2\right)\left(E(\theta)^2\overline{\theta}^2-\beta_i\beta_j\Delta^2\right)}>0. \tag{A.17}$$

Hence $E_{\delta_j^*}\left\{\widetilde{\pi}_i(\underline{\theta};\underline{\theta},\delta_j^*)\right\}>E_{\delta_j^*}\left\{\pi_i(\underline{\theta};\varnothing,\delta_j^*)\right\}$. This completes the proof.□

A.2.3 Proof of Proposition 2

Define stochastic variable $x_i\in\{E(\theta),\overline{\theta}\}$, with $\Pr[x_i=E(\theta)]=1-\Pr[x_i=\overline{\theta}]=q_i$. Observe that $E(x_i)=q_iE(\theta)+(1-q_i)\overline{\theta}=\beta_i$. Now rewrite firm i's expected profit under voluntary disclosure as follows:

$$\begin{aligned}\widetilde{\Pi}_i(r_i,r_j) &= pr_i\left[pr_j\widehat{\pi}_i(\underline{\theta},\underline{\theta})+(1-pr_j)\widetilde{\pi}_i(\underline{\theta};\underline{\theta},\varnothing)\right]+\\ &\quad +pr_j(1-pr_i)\left(q_i\widetilde{\pi}_i(\overline{\theta};\varnothing,\underline{\theta})+(1-q_i)\widetilde{\pi}_i(\varnothing;\varnothing,\underline{\theta})\right)\\ &\quad +(1-pr_j)(1-pr_i)\left(q_i\widetilde{\pi}_i(\overline{\theta};\varnothing,\varnothing)+(1-q_i)\widetilde{\pi}_i(\varnothing;\varnothing,\varnothing)\right)\end{aligned} \tag{A.18}$$

$$\begin{aligned}&= pr_i\underline{\theta}\left[pr_j\frac{1}{(\underline{\theta}+\Delta)^2}+(1-pr_j)\left(\frac{E(\theta)\overline{\theta}-\beta_j\Delta}{\underline{\theta}E(\theta)\overline{\theta}-\beta_j\Delta^2}\right)^2\right]\frac{W^2}{2} \qquad (A.19)\\ &\quad +(1-pr_i)E(\theta)\overline{\theta}\left[pr_j\frac{\beta_i(\underline{\theta}-\Delta)^2}{\left[\underline{\theta}E(\theta)\overline{\theta}-\beta_i\Delta^2\right]^2}+(1-pr_j)\frac{\beta_i(E(\theta)\overline{\theta}-\beta_j\Delta)^2}{\left(E(\theta)^2\overline{\theta}^2-\beta_i\beta_j\Delta^2\right)^2}\right]\frac{W^2}{2}.\end{aligned}$$

Rewrite firm i's expected profit under mandatory disclosure as follows:

$$\begin{aligned}
\widehat{\Pi}_i(r_i, r_j) \quad \equiv \quad & pr_i \left\{ pr_j \widehat{\pi}_i(\underline{\theta}, \underline{\theta}) + (1 - pr_j) \left[q_j \widehat{\pi}_i(\underline{\theta}, \overline{\theta}) + (1 - q_j) \widehat{\pi}_i(\underline{\theta}, \varnothing) \right] \right\} \\
& + (1 - pr_i) pr_j \left\{ q_i \widehat{\pi}_i(\overline{\theta}, \underline{\theta}) + (1 - q_i) \widehat{\pi}_i(\varnothing, \underline{\theta}) \right\} \\
& (1 - pr_i)(1 - pr_j) q_i \left[q_j \widehat{\pi}_i(\overline{\theta}, \overline{\theta}) + (1 - q_j) \widehat{\pi}_i(\overline{\theta}, \varnothing) \right] \\
& + (1 - pr_i)(1 - pr_j)(1 - q_i) \left[q_j \widehat{\pi}_i(\varnothing, \overline{\theta}) + (1 - q_j) \widehat{\pi}_i(\varnothing, \varnothing) \right] \qquad \text{(A.20)}
\end{aligned}$$

$$\begin{aligned}
= \quad & pr_i \underline{\theta} \left[pr_j \frac{1}{(\underline{\theta} + \Delta)^2} + (1 - pr_j) E_{x_j} \left\{ \left(\frac{E(\theta)\overline{\theta} - x_j \Delta}{\underline{\theta} E(\theta)\overline{\theta} - x_j \Delta^2} \right)^2 \right\} \right] \frac{W^2}{2} \\
& + (1 - pr_i) E(\theta)\overline{\theta} \left[pr_j E_{x_i} \left\{ \frac{x_i (\underline{\theta} - \Delta)^2}{\left(\underline{\theta} E(\theta)\overline{\theta} - x_i \Delta^2 \right)^2} \right\} + \right. \\
& \left. + (1 - pr_j) E_{x_i} \left(E_{x_j} \left\{ \frac{x_i \left(E(\theta)\overline{\theta} - x_j \Delta \right)^2}{\left(E(\theta)^2 \overline{\theta}^2 - x_i x_j \Delta^2 \right)^2} \right\} \right) \right] \frac{W^2}{2}. \qquad \text{(A.21)}
\end{aligned}$$

Since function $F_1(y) \equiv \left(\frac{E(\theta)\overline{\theta} - y\Delta}{\underline{\theta} E(\theta)\overline{\theta} - y\Delta^2} \right)^2$ is convex in y for all $y > 0$ and $\underline{\theta} \geq 3\Delta$, we obtain: $E_{x_j} \{F_1(x_j)\} > F_1(\beta_j)$. Function $F_2(z) \equiv \frac{z(\underline{\theta} - \Delta)^2}{\left(\underline{\theta} E(\theta)\overline{\theta} - z\Delta^2 \right)^2}$ is convex in z for all $z > 0$, and therefore: $E_{x_i} \{F_2(x_i)\} > F_2(\beta_i)$. Finally define the following function:

$$F_0(y, z) \equiv \frac{y \left(E(\theta)\overline{\theta} - z\Delta \right)^2}{\left(E(\theta)^2 \overline{\theta}^2 - yz\Delta^2 \right)^2}. \qquad \text{(A.22)}$$

It is straightforward to show that for all $y, z \in [E(\theta), \overline{\theta}]$ and $\underline{\theta} \geq 3\Delta$: F_0 is convex in z (i.e. $\partial^2 F_0(y, z)/\partial z^2 > 0$). We therefore obtain that: $E_{x_i} \left(E_{x_j} \{F_0(x_i, x_j)\} \right) > E_{x_i} \left(F_0(x_i, \beta_j) \right)$. Furthermore F_0 is clearly convex in y ($\partial^2 F_0(y, z)/\partial y^2 > 0$) for all $y, z \in [E(\theta), \overline{\theta}]$, and therefore: $E_{x_i} \left(F_0(x_i, \beta_j) \right) > F_0(\beta_i, \beta_j)$. From these inequalities and the inspection of the expected profit functions we conclude that $\widehat{\Pi}_i(r_i, r_j) \geq \widetilde{\Pi}_i(r_i, r_j)$ for all (r_i, r_j), which completes the proof.□

A.3 Knowledge Spillovers

In this part of the Appendix we prove propositions 3 and 4, respectively.

A.3.1 Proof of Proposition 3

(i) The proof is straightforward.

(ii) Under mandated disclosure the first derivative of firm i's expected profit with respect to the knowledge spillover equals the following (if $r_i = r_j = r$):

$$\begin{aligned}
\frac{\partial \widehat{\Pi}_i^\kappa(r,r)}{\partial \kappa} &= pr(1-p)r\left(\frac{\partial \widehat{\pi}_i^\kappa(\underline{\theta},\overline{\theta})}{\partial \kappa} + \frac{\partial \widehat{\pi}_i^\kappa(\overline{\theta},\underline{\theta})}{\partial \kappa}\right) + pr(1-r)\left(\frac{\partial \widehat{\pi}_i^\kappa(\underline{\theta},\varnothing)}{\partial \kappa} + \frac{\partial \widehat{\pi}_i^\kappa(\varnothing,\underline{\theta})}{\partial \kappa}\right) \\
&= pr(1-p)r\frac{(\overline{\theta}-\underline{\theta})(\underline{\theta}-\Delta)\left[\underline{\theta}\theta^\kappa(\overline{\theta},\underline{\theta})(\underline{\theta}-3\Delta)+(3\underline{\theta}-\Delta)\Delta^2\right]}{2\left(\underline{\theta}\theta^\kappa(\overline{\theta},\underline{\theta})-\Delta^2\right)} + \\
&\quad pr(1-r)\frac{(E(\theta)-\underline{\theta})(\underline{\theta}-\Delta)\left[\underline{\theta}\theta^\kappa(\varnothing,\underline{\theta})(\underline{\theta}-3\Delta)+(3\underline{\theta}-\Delta)\Delta^2\right]}{2\left(\underline{\theta}\theta^\kappa(\varnothing,\underline{\theta})-\Delta^2\right)} > 0, \quad \text{(A.23)}
\end{aligned}$$

for all $\underline{\theta} \geq 3\Delta$. Under voluntary disclosure we obtain the following for $r_i = r_j = r$ and $q \equiv \frac{(1-p)r}{1-pr}$:

$$\begin{aligned}
\frac{\partial \widetilde{\Pi}_i^\kappa(r,r)}{\partial \kappa} &= pr(1-pr)\left[\frac{\partial \widetilde{\pi}_i^\kappa(\underline{\theta};\underline{\theta},\varnothing)}{\partial \kappa} + \left(q\frac{\partial \widetilde{\pi}_i^\kappa(\overline{\theta};\varnothing,\underline{\theta})}{\partial \kappa} + (1-q)\frac{\partial \widetilde{\pi}_i^\kappa(\varnothing;\varnothing,\underline{\theta})}{\partial \kappa}\right)\right] \\
&= pr(1-pr)\frac{\partial}{\partial \kappa}\left(\frac{\frac{1}{2}\underline{\theta}\left[\theta^\kappa(\varnothing,\underline{\theta})\theta^\kappa(\overline{\theta},\underline{\theta})-\beta^\kappa\Delta\right]^2}{\left[\underline{\theta}\theta^\kappa(\varnothing,\underline{\theta})\theta^\kappa(\overline{\theta},\underline{\theta})-\beta^\kappa\Delta^2\right]^2}\right) + \\
&\quad + pr(1-pr)\frac{\partial}{\partial \kappa}\left(\frac{\frac{1}{2}\beta^\kappa\theta^\kappa(\varnothing,\underline{\theta})\theta^\kappa(\overline{\theta},\underline{\theta})(\underline{\theta}-\Delta)^2}{\left[\underline{\theta}\theta^\kappa(\varnothing,\underline{\theta})\theta^\kappa(\overline{\theta},\underline{\theta})-\beta^\kappa\Delta^2\right]^2}\right) \quad \text{(A.24)} \\
&= pr(1-rp)\frac{\left[\underline{\theta}\theta^\kappa(\varnothing,\underline{\theta})\theta^\kappa(\overline{\theta},\underline{\theta})(\underline{\theta}-3\Delta)+\beta^\kappa(3\underline{\theta}-\Delta)\Delta^2\right]L(\kappa)(\underline{\theta}-\Delta)}{2\left[\underline{\theta}\theta^\kappa(\varnothing,\underline{\theta})\theta^\kappa(\overline{\theta},\underline{\theta})-\beta^\kappa\Delta^2\right]^3},
\end{aligned}$$

with

$$\begin{aligned}
L(\kappa) &\equiv \underline{\theta}(E(\theta)\overline{\theta}+\underline{\theta}\beta)+(E(\theta)-\underline{\theta})(\overline{\theta}-\underline{\theta})\left[(1-\kappa)^2\beta-\kappa^2\underline{\theta}\right] \quad \text{(A.25)} \\
&\geq \underline{\theta}\left[(E(\theta)\overline{\theta}+\underline{\theta}\beta)-(E(\theta)-\underline{\theta})(\overline{\theta}-\underline{\theta})\right] = \underline{\theta}\left[E(\theta)+\beta+\overline{\theta}-\underline{\theta}\right] > 0.
\end{aligned}$$

Hence $\partial \widetilde{\Pi}_i^\kappa(r,r)/\partial \kappa > 0$, for all $\underline{\theta} \geq 3\Delta$, which completes the proof.□

A.3.2 Proof of Proposition 4

(i) We distinguish two deviations from the vaporware disclosure equilibrium. First consider firm i with high R&D cost. As in the proof of proposition 1, we can show that this firm does not have an incentive to disclose its cost. We obtain this result simply by replacing $\widetilde{D}_i(\overline{\theta};\varnothing,\underline{\theta})$ and $\widehat{D}_i(\overline{\theta},\underline{\theta})$ with $\widetilde{D}_i^\kappa(\overline{\theta};\varnothing,\underline{\theta})$ and $\widehat{D}_i^\kappa(\overline{\theta},\underline{\theta})$, respectively, in the first part of the proof of proposition 1, and by verifying that $\widetilde{D}_i^\kappa(\overline{\theta};\varnothing,\underline{\theta}) > \widehat{D}_i^\kappa(\overline{\theta},\underline{\theta})$ for all κ. Second consider the incentives of firm i to conceal low R&D cost, given beliefs consistent with vaporware disclosure. The expressions are similar to the expressions in the second part of the proof of proposition 1. The firm expects the following profit from disclosure:

$$E_{\delta_j^*}\left\{\widetilde{\pi}_i^{\kappa}(\underline{\theta};\underline{\theta},\delta_j^*)\right\} = \frac{1}{2}\underline{\theta}\left(pr_j\widetilde{D}_i(\underline{\theta};\underline{\theta},\underline{\theta})^2 + (1-pr_j)\widetilde{D}_i^{\kappa}(\underline{\theta};\underline{\theta},\varnothing)^2\right). \tag{A.26}$$

This expected equilibrium profit decreases in spillover κ, since $\widetilde{D}_i^{\kappa}(\underline{\theta};\underline{\theta},\varnothing)$ decreases in κ. Given beliefs consistent with vaporware disclosure, the expected profit of concealment equals:

$$E_{\delta_j^*}\left\{\pi_i^{\kappa}(\underline{\theta};\varnothing,\delta_j^*)\right\} = \frac{1}{2\underline{\theta}}\left(pr_j\theta_i^{\kappa}(\overline{\theta},\underline{\theta})^2\widetilde{D}_i^{\kappa}(\overline{\theta};\varnothing,\underline{\theta})^2 + (1-pr_j)\overline{\theta}^2\widetilde{D}_i(\overline{\theta};\varnothing,\varnothing)^2\right). \tag{A.27}$$

The expected deviation profit increases in spillover κ, since:

$$\frac{\partial[\theta_i^{\kappa}(\overline{\theta},\underline{\theta})\widetilde{D}_i^{\kappa}(\overline{\theta};\varnothing,\underline{\theta})]}{\partial\kappa} = -\Delta\frac{\partial\widetilde{D}_i^{\kappa}(\underline{\theta};\underline{\theta},\varnothing)}{\partial\kappa} > 0. \tag{A.28}$$

Therefore the difference between expected equilibrium profit and deviation profit, $E_{\delta_j^*}\left\{\widetilde{\pi}_i^{\kappa}(\underline{\theta};\underline{\theta},\delta_j^*)\right\} - E_{\delta_j^*}\left\{\pi_i^{\kappa}(\underline{\theta};\varnothing,\delta_j^*)\right\}$, decreases monotonically in spillover κ. An evaluation of this profit difference for $\kappa = 1$ gives:

$$\begin{aligned} &E_{\delta_j^*}\left\{\widetilde{\pi}_i^{1}(\underline{\theta};\underline{\theta},\delta_j^*) - \pi_i^{1}(\underline{\theta};\varnothing,\delta_j^*)\right\} = \\ &(1-pr_j)\frac{1}{2}\underline{\theta}W^2\left[\left(\frac{1}{\underline{\theta}+\Delta}\right)^2 - \left(\frac{\overline{\theta}E(\theta)(E(\theta)\overline{\theta}-\beta_j\Delta)}{\underline{\theta}(E(\theta)^2\overline{\theta}^2-\beta_i\beta_j\Delta^2)}\right)^2\right] \end{aligned} \tag{A.29}$$

If there is a firm for which this profit difference is negative, vaporware disclosure is not an equilibrium disclosure rule for both firms if $\kappa = 1$. It is straightforward to verify that the condition under which the profit difference is negative reduces to the following:

$$\begin{aligned} \frac{1}{\underline{\theta}+\Delta} &< \frac{\overline{\theta}E(\theta)(E(\theta)\overline{\theta}-\beta_j\Delta)}{\underline{\theta}(E(\theta)^2\overline{\theta}^2-\beta_i\beta_j\Delta^2)} \Leftrightarrow \left(E(\theta)\overline{\theta}-\beta_j\underline{\theta}\right)\left(E(\theta)\overline{\theta}-\beta_j\Delta\right) + (\beta_i-\beta_j)\beta_j\underline{\theta}\Delta > 0 \\ &\Leftrightarrow \beta_i > \beta_j - \left(E(\theta)\overline{\theta}-\beta_j\underline{\theta}\right)\left(E(\theta)\overline{\theta}-\beta_j\Delta\right)/\beta_j\underline{\theta}\Delta. \end{aligned} \tag{A.30}$$

There is always a firm for which this condition is satisfied. (Suppose the contrary, i.e. the condition is violated for both firms. Then for $i, j = 1, 2$ and $i \neq j$ the following two inequalities should be satisfied:

$$\beta_i < \beta_j - \left(E(\theta)\overline{\theta}-\beta_j\underline{\theta}\right)\left(E(\theta)\overline{\theta}-\beta_j\Delta\right)/\beta_j\underline{\theta}\Delta < \beta_j, \tag{A.31}$$

$$\beta_j < \beta_i - \left(E(\theta)\overline{\theta}-\beta_i\underline{\theta}\right)\left(E(\theta)\overline{\theta}-\beta_i\Delta\right)/\beta_i\underline{\theta}\Delta < \beta_i. \tag{A.32}$$

But $\beta_i < \beta_j$ and $\beta_j < \beta_i$ cannot hold simultaneously.) Hence there is always a firm that strictly prefers to conceal low R&D costs if $\kappa = 1$. Since profits are continuous and monotonous, there is a critical value $\kappa^* < 1$ such that for all $\kappa > \kappa^*$ there is a firm for which concealing low cost is a profitable deviation, given beliefs consistent with vaporware disclosure. And for all $\kappa \leq \kappa^*$ vaporware disclosure is an equilibrium disclosure strategy.

(ii) Suppose condition C.1 is satisfied for both firms. Under full concealment the firms' equilibrium R&D investments $D^o(.)$ and profits π^o are determined in the proof of lemma 3 (ii). As in part (i), consider two deviations from the full concealment equilibrium. First consider the incentive of a high-cost firm i to unilaterally disclose its cost. After this unilateral disclosure the firms' R&D investments are determined by the following first-order conditions:

$$\overline{\theta} D_i = W - \left(r_j p D_j(\underline{\theta}) + r_j(1-p) D_j(\overline{\theta}) + (1-r_j) D_j(\varnothing) \right) \Delta, \tag{A.33}$$

$$\theta^E(\Theta_j) D_j(\Theta_j) = W - D_i \Delta, \text{ for } \Theta_j \in \{\underline{\theta}, \overline{\theta}, \varnothing\}. \tag{A.34}$$

which determines firm i's investment:

$$D_i = \frac{\underline{\theta} E(\theta) \left(\underline{\theta} E(\theta) \overline{\theta} - \alpha_j \Delta \right) W}{\underline{\theta}^2 E(\theta)^2 \overline{\theta}^2 - \underline{\theta} E(\theta) \alpha_j \Delta^2} < D_i^o(\overline{\theta}), \text{ since } \alpha_i > \underline{\theta} E(\theta). \tag{A.35}$$

Therefore disclosure of high costs is not a profitable unilateral deviation from full concealment. Second consider firm i's incentive to disclose low R&D costs. After firm i discloses its low cost, firms R&D investments are determined by the following first-order conditions:

$$\underline{\theta} D_i = W - \left(r_j p D_j^o(\underline{\theta}) + r_j(1-p) D_j^o(\overline{\theta}) + (1-r_j) D_j^o(\varnothing) \right) \Delta, \tag{A.36}$$

$$\text{and } \theta^\kappa(\Theta_j, \underline{\theta}) D_j(\Theta_j) = W - D_i \Delta, \text{ for } \Theta_j \in \{\underline{\theta}, \overline{\theta}, \varnothing\}. \tag{A.37}$$

which results in the following equilibrium R&D investment and profit for firm i:

$$D_i(\kappa) = \frac{\left(\underline{\theta} \theta^\kappa(\varnothing, \underline{\theta}) \theta^\kappa(\overline{\theta}, \underline{\theta}) - \alpha_j^\kappa \Delta \right) W}{\underline{\theta}^2 \theta^\kappa(\varnothing, \underline{\theta}) \theta^\kappa(\overline{\theta}, \underline{\theta}) - \alpha_j^\kappa \Delta^2}, \text{ and} \tag{A.38}$$

$$\pi_i(\kappa) = \frac{1}{2} \underline{\theta} D_i(\kappa)^2, \text{ respectively,} \tag{A.39}$$

where α_j^κ is α_j with $E(\theta)$ and $\overline{\theta}$ replaced by $\theta^\kappa(\varnothing, \underline{\theta})$ and $\theta^\kappa(\overline{\theta}, \underline{\theta})$, respectively. It is intuitive and straightforward to show that investment $D_i(\kappa)$, and consequently expected profit $\pi_i(\kappa)$, is decreasing in κ. For $\kappa = 0$ we already showed in lemma 3

(ii) that unilateral disclosure of low costs is profitable. If all information spills over from the disclosing firm (i) to the concealing firm (j), i.e. $\kappa = 1$, unilateral deviation from full concealment is not profitable if $D_i^o(\underline{\theta}) > D_i(1) = \widehat{D}_i(\underline{\theta}, \underline{\theta})$, which holds under condition C.1. Since profits are continuous and monotonous in spillover κ, there is a critical value $\kappa^o \in (0, 1)$ such that for all $\kappa < \kappa^o$ there is a firm for which disclosing low cost is a profitable deviation, given beliefs consistent with full concealment. And for all $\kappa \geq \kappa^o$ full concealment is an equilibrium disclosure strategy. This completes the proof of the proposition. $\square$

A.4 Endogenous Information Acquisition

This part of the Appendix proves propositions 5 and 6, respectively.

A.4.1 Proof of Proposition 5

For the comparison between joint-profit-maximizing and equilibrium information acquisition investments we need to compare marginal information acquisition revenues under total-profit-maximization and mandated disclosure. We obtain overinvestment in information acquisition when the marginal revenue in equilibrium exceeds marginal revenue under total-profit-maximization. Define the following function:

$$H_i(\theta_i, \theta_j) \equiv \sum_{\ell=1}^{2} \overline{\pi}_\ell(\theta_i, \theta_j) - \widehat{\pi}_i(\theta_i, \theta_j) = \frac{W}{2}\left(\frac{\theta_i + \theta_j - 4\Delta}{\theta_i\theta_j - 4\Delta^2} - \frac{\theta_i(\theta_j - \Delta)^2}{(\theta_i\theta_j - \Delta^2)^2}\right) \tag{A.40}$$

A sufficient condition for overinvestment by firm i is then that for all R_j:

$$R_j E_{\theta_j}\left[E_{\theta_i}\left\{H_i(\theta_i, \theta_j)\right\} - H_i(E(\theta), \theta_j)\right] + (1 - R_j)\left[E_{\theta_i}\left\{H_i(\theta_i, E(\theta))\right\} - H_i(E(\theta), E(\theta))\right] < 0. \tag{A.41}$$

If function H_i is concave in θ_i for all θ_j, then this sufficient condition is met for any R_j and p. The second-order derivative of H_i towards θ_i is:

$$\frac{\partial^2 H_i(\theta_i, \theta_j)}{\partial \theta_i^2} = W\theta_j\left(\frac{(\theta_j - 2\Delta)^2}{(\theta_i\theta_j - 4\Delta^2)^3} - \frac{(\theta_j - \Delta)^2(\theta_i\theta_j + 2\Delta^2)}{(\theta_i\theta_j - \Delta^2)^4}\right). \tag{A.42}$$

We evaluate this function in $(\theta_i, \theta_j) = (\widetilde{\theta}_i + 3\Delta, \widetilde{\theta}_j + 3\Delta)$, with $\widetilde{\theta}_\ell \geq 0$ for $\ell = i, j$, which gives:

$$\begin{aligned}
\left.\frac{\partial^2 H_i(\theta)}{\partial \theta_i^2}\right|_{\theta=\widetilde{\theta}+3\Delta} &= W(\widetilde{\theta}_j + 3\Delta)\left(\frac{(\widetilde{\theta}_j + \Delta)^2}{[(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) - 4\Delta^2]^3}\right. \\
&\quad \left. - \frac{(\widetilde{\theta}_j + 2\Delta)^2[(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) + 2\Delta^2]}{[(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) - \Delta^2]^4}\right) \\
&= \frac{W(\widetilde{\theta}_j + 3\Delta) h_i(\widetilde{\theta})}{[(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) - 4\Delta^2]^3[(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) - \Delta^2]^4},
\end{aligned} \tag{A.43}$$

with

$$\begin{aligned}
h_i(\widetilde{\theta}) &= (\widetilde{\theta}_j + \Delta)^2[(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) - \Delta^2]^4 + \\
&\quad -(\widetilde{\theta}_j + 2\Delta)^2[(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) + 2\Delta^2][(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta) - 4\Delta^2]^3 \\
&= -\Delta\left[\widetilde{\theta}_i^4(\widetilde{\theta}_j + 3\Delta)^4(2\widetilde{\theta}_j + 3\Delta) + 2\Delta^2\widetilde{\theta}_i^3(\widetilde{\theta}_j + 3\Delta)^3(\widetilde{\theta}_j + 2\Delta) + \right. \\
&\quad + 2\Delta\widetilde{\theta}_i^2(\widetilde{\theta}_i + 3\Delta)(\widetilde{\theta}_j + 3\Delta)^3(9\widetilde{\theta}_j^2 + 36\Delta\widetilde{\theta}_j + 32\Delta^2) + \\
&\quad + 2\Delta^3\widetilde{\theta}_i(\widetilde{\theta}_j + 3\Delta)(27\widetilde{\theta}_j^4 + 270\Delta\widetilde{\theta}_j^3 + 999\Delta^2\widetilde{\theta}_j^2 + 1580\Delta^3\widetilde{\theta}_j + 876\Delta^4) \\
&\quad \left. + \Delta^5(27\widetilde{\theta}_j^4 + 378\Delta\widetilde{\theta}_j^3 + 1575\Delta^2\widetilde{\theta}_j^2 + 2564\Delta^3\widetilde{\theta}_j + 1404\Delta^4)\right].
\end{aligned} \tag{A.44}$$

Since $h_i(\widetilde{\theta}) < 0$ for all $\widetilde{\theta} \geq 0$, function H_i is concave in θ_i, for all $\theta_i, \theta_j \geq 3\Delta$. This completes the proof.□

A.4.2 Proof of Proposition 6

We show that in equilibrium firms invest more under voluntary disclosure than under mandatory disclosure, by showing that marginal information acquisition investments under voluntary disclosure exceed those under mandatory disclosure. We focus on symmetric information acquisition equilibria, $r_i = R_i = R$ for $i = 1, 2$. Rewrite the marginal information acquisition revenues under mandatory disclosure as in expression (7.8). Inequality $\widetilde{\Psi}(\underline{\theta}) > \widehat{\Psi}(\underline{\theta})$ follows directly from lemma 2, since:

$$\widetilde{D}_i(\underline{\theta}; \underline{\theta}, \underline{\theta}) = \widehat{D}_i(\underline{\theta}, \underline{\theta}),\ \widetilde{D}_i(\overline{\theta}; \varnothing, \underline{\theta}) \geq \widehat{D}_i(\overline{\theta}, \underline{\theta}), \text{ and } \widetilde{D}_i(\varnothing; \varnothing, \underline{\theta}) \leq \widehat{D}_i(\varnothing, \underline{\theta}). \tag{A.45}$$

In the remainder of this proof we show that for $\overline{\theta}$ close to $\underline{\theta}$ and given $\Theta_j \neq \underline{\theta}$, expected marginal information acquisition revenues under voluntary disclosure exceed those under mandated disclosure, i.e. $K(R; \overline{\theta}) > 0$, with:

$$K(R; \overline{\theta}) \equiv \widetilde{\Psi}(\varnothing) - \left(\frac{(1-p)R}{1-pR}\widehat{\Psi}(\overline{\theta}) + \frac{1-R}{1-pR}\widehat{\Psi}(\varnothing)\right). \tag{A.46}$$

First we show that for extreme investment level $R = 0$ the inequality holds. From lemma 2 (ii.b) we conclude that for $K(0;\overline{\theta}) > 0$, since:

$$\widetilde{\Psi}(\varnothing) = p\underline{\theta}\widehat{D}_i(\underline{\theta},\varnothing)^2 + (1-p)\overline{\theta}\frac{E(\theta)^2}{\overline{\theta}^2}\widehat{D}_i(\varnothing,\varnothing)^2 - E(\theta)\widehat{D}_i(\varnothing,\varnothing)^2 > \widehat{\Psi}(\varnothing). \quad \text{(A.47)}$$

Second we show that the difference between marginal information acquisition revenues under voluntary and mandated disclosure increases in R, if $\overline{\theta}$ is close to $\underline{\theta}$. Given that $K(0;\overline{\theta}) > 0$, it suffices to show that for $\overline{\theta}$ sufficiently close to $\underline{\theta}$, $\partial K(R;\overline{\theta})/\partial R > 0$ to prove that $K(R;\overline{\theta}) > 0$ for all R. It is straightforward to show that:

$$\frac{\partial K(R;\overline{\theta})}{\partial R} = \frac{1-p}{(1-pR)^2}\left(\widetilde{k}(R;\overline{\theta}) - \widehat{k}(\overline{\theta})\right), \quad \text{(A.48)}$$

with

$$\widetilde{k}(R;\overline{\theta}) \equiv 2\Delta\overline{\theta}E(\theta)(\overline{\theta}-E(\theta))\left(\frac{p\underline{\theta}(\underline{\theta}-\Delta)(E(\theta)\overline{\theta}-\beta\Delta)}{(\underline{\theta}E(\theta)\overline{\theta}-\beta\Delta^2)^3} - \frac{\overline{\theta}-(1-p)E(\theta)}{(E(\theta)\overline{\theta}+\beta\Delta)^3}\right)\frac{1}{2}W^2, \quad \text{(A.49)}$$

and

$$\widehat{k}(\overline{\theta}) \equiv \widehat{\Psi}(\overline{\theta}) - \widehat{\Psi}(\varnothing). \quad \text{(A.50)}$$

It is easily verified that $\lim_{\overline{\theta}\downarrow\underline{\theta}} \frac{\partial K(R;\overline{\theta})}{\partial R} = 0$ for any R. For $\partial K(R;\overline{\theta})/\partial R > 0$ to hold for some $\overline{\theta} > \underline{\theta}$, it suffices to show that $\lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial^2 K(R;\overline{\theta})}{\partial\overline{\theta}\partial R}\right) > 0$. For then there is an $\varepsilon > 0$ such that $\partial K(R;\overline{\theta})/\partial R > 0$ for $\overline{\theta} \in (\underline{\theta}, \underline{\theta}+\varepsilon]$. When we differentiate $\partial K(R;\overline{\theta})/\partial R$ to $\overline{\theta}$ and evaluate it in $\overline{\theta} \downarrow \underline{\theta}$, we obtain the following:

$$\begin{aligned}
\lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial^2 K(R;\overline{\theta})}{\partial\overline{\theta}\partial R}\right) &= \lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial^2 \widetilde{k}(R;\overline{\theta})}{\partial\overline{\theta}\partial R}\right) - \lim_{\overline{\theta}\downarrow\underline{\theta}}\left(\frac{\partial^2 \widehat{k}(\overline{\theta})}{\partial\overline{\theta}\partial R}\right) \\
&= \frac{2\Delta p^2[\underline{\theta}-(\underline{\theta}-\Delta)]}{(\underline{\theta}-\Delta)(\underline{\theta}+\Delta)^3} - \frac{2\Delta p\underline{\theta}[-p-(1-p)+1]}{(\underline{\theta}-\Delta)(\underline{\theta}+\Delta)^3} \\
&= \frac{2\Delta^2 p^2}{(\underline{\theta}-\Delta)(\underline{\theta}+\Delta)^3} > 0. \qquad \text{(A.51)}
\end{aligned}$$

This final result is sufficient to show that K is positive for all R, which completes the proof.□

A.4.3 Overall Profit Comparison

For $r_i = r_j = R$, firm i's expected R&D profit reduces to the following:

$$\begin{aligned}
\widehat{\Pi}_i^o(R) \equiv \widehat{\Pi}_i(R,R) = \quad & RE_{\theta_i}\left\{RE_{\theta_j}[\widehat{\pi}_i(\theta_i,\theta_j)] + (1-R)\widehat{\pi}_i(\theta_i,\varnothing)\right\} + \\
& +(1-R)\left(RE_{\theta_j}[\widehat{\pi}_i(\varnothing,\theta_j)] + (1-R)\widehat{\pi}_i(\varnothing,\varnothing)\right). \quad \text{(A.52)}
\end{aligned}$$

The first derivative of this function towards R equals:

$$\begin{aligned}
&\frac{d\widehat{\Pi}_i^o(R)}{dR} = R\left(2E_\theta\left\{\widehat{\pi}_i(\theta_i,\theta_j)\right\} - E_{\theta_i}\left\{\widehat{\pi}_i(\theta_i,\varnothing)\right\} - E_{\theta_j}\left\{\widehat{\pi}_i(\varnothing,\theta_j)\right\}\right) + \\
&+(1-R)\left(E_{\theta_i}\left\{\widehat{\pi}_i(\theta_i,\varnothing)\right\} + E_{\theta_j}\left\{\widehat{\pi}_i(\varnothing,\theta_j)\right\} - 2\widehat{\pi}_i(\varnothing,\varnothing)\right) \\
= \; & R\left(E_{\theta_j}\left\{E_{\theta_i}\left(\frac{\theta_i(\theta_j-\Delta)^2+\theta_j(\theta_i-\Delta)^2}{(\theta_i\theta_j-\Delta^2)^2}\right) - \frac{E(\theta)(\theta_j-\Delta)^2+\theta_j(E(\theta)-\Delta)^2}{(E(\theta)\theta_j-\Delta^2)^2}\right\}\right) + \\
&+(1-R)\left(E_{\theta_i}\left\{\frac{\theta_i(E(\theta)-\Delta)^2+E(\theta)(\theta_i-\Delta)^2}{(\theta_iE(\theta)-\Delta^2)^2}\right\} - \frac{2E(\theta)(E(\theta)-\Delta)^2}{(E(\theta)^2-\Delta^2)^2}\right). \qquad \text{(A.53)}
\end{aligned}$$

Since the function $\frac{x(y-\Delta)^2+y(x-\Delta)^2}{(xy-\Delta^2)^2}$ is convex in x for all $y \geq 3\Delta$, we obtain $d\widehat{\Pi}_i^o(R)/dR > 0$.□

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