

# Strategic Cash Holdings and R&D Competition: Theory and Evidence

## **Abstract**

We examine theoretically and empirically the determinants of cash holdings by innovating firms. Our model highlights an important strategic role that cash plays in affecting the development and implementation of innovation in the presence of competition in the market for R&D-intensive products. Firms' equilibrium cash holdings are shown to depend on the degree of innovation efficiency in firms' industries, on the intensity of competition in post-R&D output markets, on the structure of the industries in which firms innovate, and on the interactions of these factors with the costs of obtaining external financing. In addition, the model provides a possible explanation for the temporal increase in cash holdings, particularly among R&D-intensive firms. Our empirical evidence demonstrates that financing costs, innovation efficiency, intensity of competition, and industry structure are indeed associated with firms' observed cash-to-assets ratios in ways that are generally consistent with the model's predictions.

# 1. Introduction

In this paper we examine theoretically and empirically the determinants of cash holdings of innovating firms. Understanding which factors affect the cash holdings of research-intensive firms has become especially important for at least three reasons. First, firms' cash holdings (normalized by assets) have more than doubled on average in the last three decades (e.g., Bates, Kahle and Stulz (2009)). This finding is surprising in light of the financial innovation that has taken place in the last thirty years, since financial innovation is thought to reduce the magnitude of transaction costs (e.g., Grinblatt and Longstaff (1992)), the extent of agency conflicts (e.g., Ross (1989)), and, in general, the costs of obtaining external financing and the resulting marginal benefits of holding cash (e.g., Miller (1986)).

Second, this temporal increase in average cash holdings is driven almost solely by innovating firms, i.e. by firms that invest relatively heavily in research and development (R&D). In particular, we document that the mean cash-to-assets ratio of firms belonging to the top quintile of R&D-to-assets ratio has increased from approximately 10% to approximately 50% between 1976 and 2010. During the same time period, the mean cash-to-assets ratio of firms belonging to the bottom R&D-to-assets quintile has increased from about 12% to about 17%. This pattern of substantially larger increase in mean cash holdings among R&D-intensive firms seems pervasive as it holds in subsets of manufacturing industries, services industries, and all other industries. Also, this finding is not due to the "composition effect": while it is true that the average size and age of a public firm have decreased over time, the documented increase in cash holdings of innovative firms is robust to controlling for firm size and/or age. Third, the same time period has been characterized by increased R&D investment by innovating firms. The mean R&D-to-assets ratio in the top R&D-to-assets quintile has increased from 10% to 45%, while remaining constant at zero in the bottom R&D-to-assets quintile.

The cash literature has identified two main motives for hoarding cash. The first is the precautionary savings motive. Firms may want to have substantial cash holdings because of the possibility of a future need for liquidity, arising, for example, from operating losses or from uncertain future expenditures

(e.g., Gamba and Triantis (2008) and Bolton, Chen and Wang (2011)). This idea dates back to Keynes (1936), who emphasizes the potential costs of obtaining external financing and of converting illiquid assets into cash. Consistent with this argument, Opler, Pinkowitz, Stulz and Williamson (1999) and Han and Qiu (2007) find a positive relation between firms' cash holdings and their cash flow volatility. In the context of cash holdings of innovating firms, Kamien and Schwartz (1978) are the first to demonstrate theoretically the increased need for cash by firms engaging in large innovations, and Himmelberg and Petersen (1994) are the first to examine the relation between R&D investments and internal finance and to conclude that "because of capital market imperfections, the flow of internal finance is the principal determinant of the rate at which small, high-tech firms acquire technology through R&D."

The second potential reason for holding cash is the "deep-pockets" argument (e.g., Telser (1966), Benoit (1984), Baskin (1987), and Bolton and Scharfstein (1990)), according to which firms may choose high cash holdings in order to ensure that they can withhold cutthroat competition, the threat of which may drive potential entrants and less well-capitalized incumbents out of the industry. Consistent with the deep-pockets theory, the empirical studies of Frésard (2010) and Boutin, Cestone, Fumagalli, Pica and Serrano-Velarde (2011) suggest that cash holdings are indeed positively associated with market share gains.

While both precautionary savings and deep-pockets motives for holding cash are important for firms' equilibrium cash holding choices, we believe that the strategic motive for hoarding cash that follows from the deep-pockets argument is crucial in the context of innovating firms. First, such firms derive most of their value from investment opportunities and are, thus, less reliant on cash flows from existing assets. Second, because of the relatively high degree of information asymmetry between innovating firms and outsiders, firms investing in innovative products may face a larger wedge between the costs of external and internal finance (e.g., Myers and Majluf (1984) and Diamond and Verrecchia (1991)). Thus, the importance of strategic cash holdings, which firms can use to discourage their

competitors from developing and implementing innovative ideas, may be especially high for innovating firms. The strategic motive for holding cash has arguably become more important in recent years than ever before due to the seeming temporal increase in the intensity of competition in output markets. For example, Bils and Klenow (2004) report relatively more frequent product market price changes (less sticky prices) in recent years,<sup>1</sup> and Irvine and Pontiff (2009) document a positive trend in firm turnover.

Surprisingly, despite the high importance of strategic considerations for innovating firms, the literature examining strategic choices of cash by such firms is limited. To our knowledge, the only paper that explicitly examines the strategic effects of cash holdings on firms' R&D strategies and outcomes is the recent work by Schroth and Szalay (2010), who show theoretically and empirically that firms that hold more cash are more likely to win patent races than those with lower cash holdings. However, optimal cash holdings is not the focus of Schroth and Szalay's work, and, therefore, they take firms' cash holdings as given. In contrast, our analysis focuses on the determinants of equilibrium cash holdings of innovating firms.

We analyze firms' choices of cash holdings using a static model with three stages. Firms first decide how much cash to raise and how much of it to devote to investments in innovation (and how much of it to hoard for future use). The likelihood of innovation success is increasing in the level of R&D investment. Second, firms that innovate successfully decide whether to implement their innovations by investing in production facilities using the saved internal cash and external cash that they can raise by paying proportional issuance cost. In the third stage, firms that have decided to implement their innovations compete in the output market. Firms' expected profits depend on the number of firms that have successfully innovated and that have decided to implement their innovations.

Cash plays a strategic role in the second stage of the game. A firm with relatively high cash holdings is more likely to invest in innovation than a firm with relatively low cash holdings because internal

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<sup>1</sup>Price stickiness is negatively associated with demand elasticity and, as a result, with competition (e.g., Barro (1972)).

funds are cheaper than external ones. An investment by a firm in a production facility reduces the expected output market profits of the firm's competitors and, therefore, reduces the likelihood that the firm's rivals would find implementing their innovations attractive. Thus, a firm may decide to hold more cash in order to reduce the probability that other innovating firms (rivals) would build production facilities, indirectly benefiting the firm by increasing its expected profit in the output market. Strategic cash-holding choices are similar in spirit to strategic debt choices (e.g., Brander and Lewis (1986), Maksimovic (1988) and Showalter (1995)) and strategic going-public decisions in Chod and Lyandres (2011).

Importantly, in the context of multi-stage investment, in which firms first invest in R&D and then potentially invest in the implementation of their successful innovations, the strategic role of cash is not limited to affecting competitors' investments in the innovation implementation stage. Value-maximizing firms that are aware of the effects of cash on the expected profitability of the future implementation of innovation rationally reduce their R&D investments in response to increases in their rivals' cash holdings, amplifying the strategic effect of cash.

The illustration of this amplification effect of deep pockets in a multi-stage investment setting is the first theoretical contribution of our model. The second contribution to the strategic cash holdings literature is that unlike existing studies that assume pre-determined industry structure, we examine strategic cash-holding choices in a situation in which firms compete in product markets whose industry structure is not known with certainty. Firms that decide how much cash to hoard and how much cash to invest in R&D do not know ex-ante how many of their rivals will succeed in their innovation projects and how many will decide to implement their innovations. Therefore, if a firm has successfully developed and implemented its innovation, the number of firms it is going to compete with in the output market is stochastic. In particular, in deciding how much cash to hoard, each innovating firm must take into account a situation in which it would become a monopolist in the output market and cash would play no strategic role.

Another contribution to the deep-pockets literature is that unlike existing models that typically assume (potential) duopolistic competition, our model allows for an arbitrary number of firms that innovate in a given industry. An analysis of the effects of initial industry structure (i.e. the number of firms that compete in innovation) on firms' equilibrium cash holdings produces non-trivial comparative statics.

Our model is capable of explaining the temporal increase in average cash holdings, particularly among R&D-intensive firms. The model demonstrates that unlike financial innovation, which reduces the costs of obtaining external funds and the incentives to hoard internal cash, technological innovation, which reduces the costs of R&D (i.e. raises innovation efficiency), raises the incentives to hold cash precisely when external financing costs are relatively low. Moreover, a combination of financial and technological innovation is more likely to lead to a larger increase in the cash-holdings of firms that are efficient in innovation (and that end up being R&D-intensive firms) than in less efficient firms. The model also shows that the intensity of output market competition, which has arguably increased over time, is positively related to optimal cash holdings, in particular among innovative firms, contributing to the temporal increase in their observed cash holdings.

In addition to providing a possible explanation for observed empirical regularities, our model results in multiple cross-sectional empirical predictions regarding determinants of firms' equilibrium cash holding choices. First, the model shows that firms' equilibrium cash holdings are increasing in innovation efficiency, i.e. in the expected likelihood of innovation success for a given level of R&D investment, for firms facing relatively low costs of external financing, while cash holdings are decreasing in innovation efficiency for firms with relatively expensive external financing.

The intuition is based on the trade-off between the following two effects. First, higher innovation efficiency increases the optimal level of R&D investment and raises the likelihood that cash would be useful for strategic purposes in the stage in which successful firms decide whether to implement their innovations. Second, increasing innovation efficiency increases expected firm value for any given

level of cash holdings and R&D investment, reducing the resulting cash-to-value ratio. When external financing costs are relatively low, the first effect dominates. When external funds are relatively expensive, equilibrium firm value is more sensitive to innovation efficiency than equilibrium cash holdings are, since a firm's incentives to hoard cash are relatively high even for low levels of innovation efficiency.

Second, the model demonstrates that equilibrium cash holdings may increase or decrease in the intensity of product market competition. In most situations, cash holdings are expected to be increasing in the intensity of competition because the strategic benefit of cash holdings increases in competition intensity. This logic is similar to that in Lyandres (2006), who shows that the strategic benefit of debt and equilibrium leverage increase in the intensity of product market competition.

The relation between competition intensity and equilibrium cash holdings is reversed for firms that have access to relatively inexpensive external financing and have relatively low innovation efficiency. The reason is that when innovation efficiency is low, optimal R&D spending by all firms is low, which results in a low likelihood of successful innovation by each firm. Thus, when innovation efficiency is low, a firm that happens to be successful in innovation is likely to become a monopolist in the output market, in which case cash would play no strategic role. The likelihood of not needing cash for strategic reasons increases in the degree of product market competition because the latter reduces expected profits from the implementation of innovation, lowering optimal investment in R&D and the likelihood of innovation success. Note that this possible negative relation between the intensity of output market competition and equilibrium cash holdings can only be obtained in a model in which the structure of the output market is stochastic; it cannot be obtained in a deep-pockets model with a predetermined (duopolistic) output market structure.

In addition, the model shows that firms' choices of cash holdings depend on the number of firms that invest in innovation in a given industry. In particular, the relation between equilibrium cash holdings and the number of industry rivals is hump-shaped. The intuition is that when the number of firms is low, if a firm succeeds in first-stage innovation, it is relatively likely to be the only successful

firm, in which case cash would play no strategic role. As the number of firms increases, the one-firm scenario in the second stage becomes increasingly unlikely, raising the likelihood of cash being useful for strategic reasons. However, as the number of firms keeps growing, each firm's expected payoff from implementing its innovation decreases, leading to lower investments in R&D and a lower likelihood of innovation success. The latter reduces the probability of needing cash in the implementation stage, lowering the marginal benefit of cash holdings. Note that only the second effect would be present in a standard deep-pockets model with no innovation development stage and no uncertainty regarding the structure of the output market. The first (positive) effect of the number of competing firms on their optimal cash holdings is due to the possibility of a monopolistic output market.

In the empirical part of the paper we test the model's predictions using data obtained from the NBER Patent Citations Data Project. We use this dataset to construct a sample of innovating firms, to identify industries in which firms innovate, and to define measures of innovation efficiency and of the intensity of competition among firms competing in related areas. We use this dataset to examine the empirical relations between firms' cash holdings and proxies for the costs of external funds, innovation efficiency, intensity of output market competition, and industry structure.

Our empirical results are generally consistent with the model's comparative statics and, more generally, with the strategic role of cash in R&D competition. First, innovation efficiency is positively related to cash holdings for relatively financially unconstrained firms, while it is negatively related to cash holdings for relatively constrained firms. Second, the intensity of product market competition is positively related to firms' observed cash holdings. Third, the relation between cash holdings and the number of firms innovating in similar areas is found to be hump-shaped. Overall, our empirical analysis shows that cash holdings have an important strategic role in a setting in which firms compete in innovation development and implementation.

The remainder of the paper is organized as follows. In the next section we present our model of strategic cash holdings in the context of competition in innovation. In Section 3 we discuss the data

and our empirical methods, and present the results of the tests of the model's predictions. Section 4 summarizes and concludes.

## 2. Model

### 2.1. Setup and assumptions

Assume that there are  $N$  firms in an industry. Each firm can invest in the research and development (R&D) of an innovative product. Each firm that succeeds in R&D can then invest in a production facility using internal and possibly external resources, and compete with other successful firms in the output market. The game has three stages. In each stage, firms make decisions simultaneously and non-cooperatively, while observing their own and their rivals' outcomes in previous stages.

In the first stage of the game, firms choose two quantities. The first is the likelihood of being successful in innovation,  $p_i$  for firm  $i$ . We assume that the cost of achieving the likelihood of succeeding in the R&D innovation of  $p_i$  equals  $\xi(p_i)$ , which is positive, increasing, and weakly convex in  $p_i$ :  $\xi(p_i) \in [0, \infty)$ ,  $\xi'(p_i) > 0$ ,  $\xi''(p_i) \geq 0$ . The second choice variable is the amount of cash holdings that is not used for R&D but that can be used for investment in a production facility in the second stage if the first-stage R&D is successful (i.e. implementation of successful innovation),  $C_i$  for firm  $i$ . Cash holdings that are not used for R&D investment earn a gross internal accumulation rate of  $r$  between the first and second stages. Thus, in the beginning of the game, firm  $i$  sells claims worth  $\xi(p_i) + C_i/r$ . The outcome of innovation (success or failure for each firm) is revealed at the end of the first stage. We denote the number of firms that have succeeded in innovation by  $n$ ,  $n \leq N$ .

In the second stage of the game, if firm  $i$  has successfully innovated, it has an option to implement its innovation by making an investment in a production facility of an exogenously determined size  $I_i$ . We assume that  $I_i$  is stochastic and has a certain distribution,  $F(I_i)$ , bounded between  $\underline{I}$  and  $\bar{I}$ . The realization of  $I_i$  occurs in the beginning of the second stage. If the realized investment cost is higher

than firm  $i$ 's cash reserves (i.e.  $I_i > C_i$ ) and if the firm decides to implement its innovation, it has to raise the difference externally and to pay proportional issuance cost  $\alpha(I_i - C_i)$ . We assume that the distribution of required investment of firm  $i$ ,  $I_i$ , is independent from the distributions of required investments of all other firms.

In the third stage,  $k$  firms,  $k \leq n$ , that have succeeded in first-stage innovation and have decided to implement their innovation in the second stage compete in a heterogenous output market á la Bertrand.<sup>2</sup> The assumption of heterogenous products allows us to accommodate different degrees of substitutability among firms' products and to derive comparative statics with respect to the intensity of product market competition. In particular, industry demand is characterized by a representative consumer with quadratic utility function

$$U(\mathbf{q}) = \mu \sum_{i=1}^k q_i - \frac{1}{2} \left( \sum_{i=1}^k q_i^2 + 2\gamma \sum_{j \neq i} q_i q_j \right), \quad (1)$$

where  $\mathbf{q}$  is the vector of consumption,<sup>3</sup>  $\mu$  and  $\gamma$  are the parameters of the consumer's utility function,  $q_i$  is consumption of good  $i$ , and  $k$  is the number of firms that were successful in R&D and decided to implement their innovations and, thus, the number of available products. This specification is typical of partial equilibrium models commonly used in the industrial organization literature (see, for example, Vives (2000)).<sup>4</sup> We impose the standard conditions:  $\mu > 0$  and  $0 < \gamma < 1$  (see Vives (2000)). Specifically,  $\gamma > 0$  implies that the goods produced are substitutes, which is reasonable for the products of firms competing in the same industry, while  $\mu > 0$  and  $\gamma < 1$  imply that the utility function is concave in each of its arguments. In what follows, we refer to  $\gamma$  as the competition intensity parameter: the closer  $\gamma$  is to one, the closer substitutes the products and the more intense the competition in the output market.

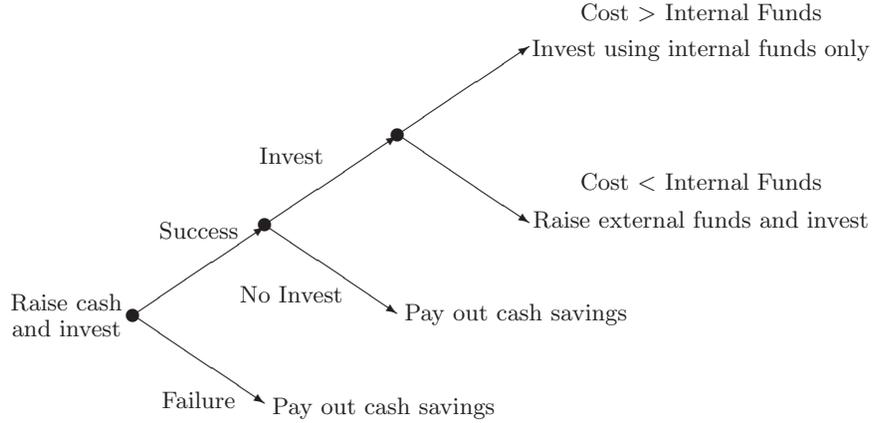
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<sup>2</sup>The specific form of product market competition is not crucial as long as equilibrium profits in the output market are decreasing in the number of competing firms.

<sup>3</sup>In what follows, bold symbols indicate vectors.

<sup>4</sup>This specification implicitly assumes that there is a numeraire good (or money), which represents the rest of the economy, and that income is large enough that the budget constraint is never binding and all income effects are captured by the consumption of the numeraire good.

**Fig. 1.** Timing of events



Firm  $i$ 's payoff in the third stage is given by

$$\pi_i(k) = q_i \eta_i - q_i^2, \quad (2)$$

where  $\eta_i$  is the equilibrium price for firm  $i$ 's product, which depends on its production quantity and also on the production quantities of its output market rivals.<sup>5</sup>

We assume that the gross discount rate between the first and the second stage,  $R$ , is higher than the internal accumulation rate of cash between the first and second stage,  $r < R$ . Since there are no savings decisions in stage 2, we assume, without loss of generality, that the discount rate and the internal accumulation rate between the second and third stages is zero. We also assume that firms' owners are risk-neutral and maximize their expected values in each stage of the game. The overall structure of the game is summarized in Figure 1.

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<sup>5</sup>Such a payoff function is a result of a Cobb-Douglas production function with one variable input (e.g., labor):  $q_i = L_i^{\frac{1}{2}}$ , where the cost of the variable input equals one. Parametric restrictions on the production function and on the consumer's utility function simplify the algebra considerably without loss of generality.

## 2.2. Solution outline

In this subsection, we outline the general solution of the model by backwards induction, starting from the third (output market competition) stage, while in the next subsection we present a more detailed solution for the case of two firms ( $N = 2$ ).

### 2.2.1. Third stage – output market competition

Equating the marginal utility that the representative consumer derives from consuming product  $i$  to its price and solving the resulting system of  $k$  equations in  $k$  unknowns (quantities) determines the demand for product  $i$  as a function of its own price and the other products' prices:

$$D_i(\vec{\eta}) = a - bp_i + c_{j \neq i} \eta_j, \quad (3)$$

where

$$a = \frac{\mu}{1 + (k-1)\gamma}, \quad b = \frac{1 + (k-2)\gamma}{[1 + (k-1)\gamma](1-\gamma)}, \quad c = \frac{\gamma}{[1 + (k-1)\gamma](1-\gamma)}.$$

Plugging in the demand function for product  $i$  in Eq. (3) into firm  $i$ 's third-stage payoff function in Eq. (2), differentiating the resulting expression with respect to  $\eta_i$  and equating the result to zero leads to firm  $i$ 's first-order conditions (F.O.C.s). Solving the resulting system of  $k$  F.O.C.s results in the following equilibrium third-stage payoff for each firm that implements its innovation, as a function of the number of firms that have decided to do so:

$$\pi^*(k) = \frac{\mu^2(1 + (k-2)\gamma)(2 + 2(k-2)\gamma - (k-1)\gamma^2)}{((4 + (5k-9)\gamma + (k^2 - 4k + 3)\gamma^2)^2)}. \quad (4)$$

Importantly, it is easy to verify that  $\pi^*(k)$  is decreasing in  $k$ .

### 2.2.2. Second stage – implementing innovations by making investments in production facilities

Assume first that firm  $i$  has succeeded in its first-stage R&D. Then it would invest in a production facility in the second stage as long as the expected third-stage payoff exceeds the cost of investment

along with potential financing cost:

$$-I_i - \max(I_i - C_i, 0)\alpha + \mathbb{E}_{i,n}(\pi^*(n)) > 0. \quad (5)$$

$\mathbb{E}_{i,n}(\pi^*(n)) = \sum_{k=1}^n \text{prob}(k)\pi^*(k)$ , where  $\pi^*(k)$  is the expected third-stage payoff conditional on  $k$  firms implementing their innovations, given in Eq. (4), and  $\text{prob}(k)$  is the probability that exactly  $k$  firms decide to make the second-stage investments. Thus, the expectation in  $\mathbb{E}_{i,n}(\pi^*(n))$  is taken over the number of firms,  $1 \leq k \leq n$ , that decide to implement their innovations (including firm  $i$ ). Therefore, firm  $i$  would invest in a production facility as long as

$$I_i < I_i^*(n, \text{Constrained}) = \frac{\mathbb{E}_{i,n}(\pi^*(n)) + C_i\alpha}{1 + \alpha} \quad \text{if } C_i \leq \mathbb{E}_{i,n}(\pi^*(n)), \quad (6)$$

$$I_i < I_i^*(n, \text{Unconstrained}) = \mathbb{E}_{i,n}(\pi^*(n)) \quad \text{if } C_i > \mathbb{E}_{i,n}(\pi^*(n)). \quad (7)$$

Firm  $i$  decides to invest in the second stage if the expected profit in the output market exceeds the investment cost in the unconstrained case (Eq. 7) and if the expected payoff exceeds the combination of investment and financing costs in the constrained case (Eq. (6)). The probability of firm  $i$  implementing its innovation,  $\omega_i$ , conditional on having succeeded in the first-stage R&D along with  $n - 1$  other firms with certain cash levels is

$$\omega_i(n) = F(I_i^*(n)). \quad (8)$$

The equilibrium investment thresholds are obtained by solving a system of  $n$  equations as in Eq. (6) and Eq. (7) in  $n$  unknowns (firms' investment thresholds), in which  $\text{prob}(k)$  is a function of the probabilities of each firm investing in production facility,  $\omega_i(n)$  for firm  $i$ .

### 2.2.3. First stage – investment in R&D and cash savings

The overall value of firm  $i$  as a function of its chosen likelihood of innovation success,  $p_i$ , and of its chosen cash holdings that can be used for second-stage investment,  $C_i$ , is given by

$$\begin{aligned}
V_i = & -(C_i/r + \xi(p_i)) + \\
& \frac{1}{R} p_i \mathbb{E}_{i,N} \left\{ \int_{\underline{I}}^{I_1^*(n, C_i, \mathbf{C}_{-i})} [\mathbb{E}_{i,n}(\pi^*(n)) dI_i + (C_i - I_i)] dI_i + \int_{I_1^*(n, C_i, \mathbf{C}_{-i})}^{\bar{I}} C_i dI_i + \right. \\
& \left. \mathbf{1}_{I_1^*(n, C_i, \mathbf{C}_{-i}) > C_i} \int_{C_i}^{I_1^*(n, C_i, \mathbf{C}_{-i})} (C_i - I_i)(1 + \alpha) dI_i \right\} + \\
& \frac{1}{R} (1 - p_i) C_i. \tag{9}
\end{aligned}$$

The first line in Eq. (9) contains the cash raised in order to be potentially used for second-stage implementation of innovation,  $C_i/r$ , and for first-stage investment in R&D,  $\xi(p_i)$ . The second and third lines in Eq. (9) represent the case in which firm  $i$  is successful in its first-stage innovation. In this case its value is an expectation taken over the number of firms that can potentially succeed in innovation,  $\mathbb{E}_{i,N}$ , of the expected firm  $i$ 's payoff,  $\mathbb{E}_{i,n}(\pi^*(n))$ , net of investment, where the expectation is taken over the number of firms that have previously succeeded in innovation. In particular, the first integral in the curly brackets represents the case in which the realized investment cost is lower than the threshold investment cost given a firm's own second-stage cash holdings,  $C_i$ , and its (successfully innovating) rivals' cash holdings,  $\mathbf{C}_{-i}$ . The second integral in the curly brackets represents the case in which the realized investment cost is too high and the firm ends up foregoing investment and paying out  $C_i$ . The third integral represents the case in which the investment cost is higher than the second-stage cash holdings but still low enough for an investment in a production facility to be profitable in expectation even though part of the investment has to be financed externally. It is pre-multiplied by the indicator variable,  $\mathbf{1}_{I_1^*(n, C_i, \mathbf{C}_{-i}) > C_i}$ , that equals one if firm  $i$ 's investment threshold for the case of  $n$  successfully innovating firms,  $I_1^*(n, C_i, \mathbf{C}_{-i})$ , is higher than the firm's second-stage cash holdings,  $C_i$ , and equals zero otherwise. Finally, the last line in Eq. (9) represents the case in which firm  $i$  is unsuccessful in innovation and is forced to distribute  $C_i$  in the second stage.

### 2.3. Two-firm case solution

In this subsection we solve the model for the case of  $N = 2$ . An analysis of the two-firm case allows us to provide simple intuition for the main driving forces of the model and of the comparative statics. In addition, under certain assumptions on functional forms, the two-firm case can be solved analytically up to the first-stage F.O.C.s. However, we verify using numerical analyses that the comparative statics derived for the case of  $N = 2$  hold in the case of  $N > 2$ . The additional assumptions on the functional forms that we make are as follows.

1) The cost of achieving a given likelihood of innovation success,  $\xi(p_i)$ , is given by

$$\xi(p_i) = -\ln\left((1-p_i)^{\frac{1}{\delta}}\right). \quad (10)$$

The cost function in Eq. (10) has the following appealing properties:  $\xi(p_i) \rightarrow 0$  when  $p_i \rightarrow 0$  and  $\xi(p_i) \rightarrow \infty$  when  $p_i \rightarrow 1$ . In addition,  $\frac{\partial \xi(p_i)}{\partial \delta} < 0$  and, therefore, in what follows we refer to  $\delta$  as the innovation efficiency parameter.

2)  $\underline{I} = 0$ ,  $\bar{I} = 1$ , and  $I_i$  is distributed uniformly:

$$I_i \sim \mathbb{U}(0, 1). \quad (11)$$

3) To simplify the algebra, we normalize  $\mu$  in a way that results in monopoly payoff,  $\pi^*(1)$ , equaling one:  $\mu = 2\sqrt{2}$ . This normalization does not lead to any loss of generality.

The third-stage payoff for a single firm,  $\pi^*(1) = 1 > \pi^*(k)$  for any  $k > 1$ , is such that a firm would not raise cash that exceeds 1 in equilibrium. Thus, in the case in which firm  $i$  is the only one to have successfully innovated in the first stage, its second-stage investment threshold is the constrained one as in Eq. (6) and equals

$$I_i^*(1, C_i) = \frac{1 + C_i \alpha}{1 + \alpha}. \quad (12)$$

The payoff of two third-stage duopolists (i.e two firms that have succeeded in R&D innovation and decided to implement their innovations) is a decreasing function of the intensity of competition,  $\gamma$ :  $\pi^*(2) = \frac{\mu^2(2-\gamma^2)}{(4+\gamma-\gamma^2)^2}$ , according to Eq. (4). The second-stage investment threshold of each of the two second-stage duopolists could be constrained, as in Eq. (6), if firm  $i$ 's chosen cash holdings,  $C_i^*$ , are lower than  $\pi^*(2)$ , or the threshold can be unconstrained if the chosen cash holdings are higher than

$\pi^*(2)$ . Therefore, in principle, there could be four potential types of equilibria, corresponding to the constrained/unconstrained second-stage investment thresholds of each of the two firms.

However, it is easy to show that there are no asymmetric equilibria in which, for example, firm 1's investment threshold is unconstrained while firm 2's threshold is constrained,  $C_1^* \geq \pi^*(2) > C_2^*$ , or vice versa. To see this, assume that an equilibrium like this exists. Note that the marginal cost of one unit of cash holdings is constant at  $\frac{R}{r} - 1$  for both firms. The marginal benefit of cash holdings equals the product of the likelihood of requiring external financing in the second stage and the proportional cost of external financing,  $\alpha$ . The marginal benefit of one unit of cash holdings is higher for firm 2. This is because firm 1's marginal benefit of cash holdings is higher than that of firm 2 whether the firms end up as second-stage monopolists or duopolists. In the former case, the marginal benefit of cash holdings for firm 1 is  $\alpha \left( F \left( \frac{1+C_1^*}{1+\alpha} \right) - F(C_1^*) \right) = \frac{\alpha}{1+\alpha} (1 - C_1^*)$ . Similarly, the marginal benefit of cash holdings for firm 2 is  $\frac{\alpha}{1+\alpha} (1 - C_2^*)$  and is higher than that of firm 1 because  $C_1^* > C_2^*$  by assumption. In the second-stage duopoly case, firm 1's marginal benefit of cash holdings is zero, since it is unconstrained, while firm 2's marginal benefit equals  $\alpha(F(I_2^*) - F(C_2^*)) > 0$ . Since the marginal benefit of cash holdings has to equal the marginal cost of cash holdings for both firms, there cannot be an equilibrium in which one of the firms is constrained in the second stage while the other is not.

Thus, there could be only two types of equilibria. In the first both firms are unconstrained in the second-stage duopoly case,  $C_1^* \geq \pi^*(2)$  and  $C_2^* \geq \pi^*(2)$ . In the second, both are constrained:  $C_1^* < \pi^*(2)$  and  $C_2^* < \pi^*(2)$ . The equilibrium depends on the marginal cost of cash holdings relative to their expected marginal benefit. If the marginal cost is very low (i.e.  $r \rightarrow R$ ), firms would choose high levels of cash holdings and would be unconstrained in the second-stage duopoly case. On the other hand, if the marginal cost of cash holdings is high enough, firms would find themselves constrained in the second-stage duopoly.

In the unconstrained case, cash holdings play no strategic role, in the sense that a firm's level of cash holdings does not impact its rival's optimal choice of cash holdings, its level of investment

in innovation, or the likelihood of exercising its second-stage investment option. Since the strategic motive for holding cash is a focus of our analysis and since we model innovating firms, which are likely to be relatively financially constrained, we concentrate on the case in which firms are constrained in the second-stage duopoly by choosing parameter values that ensure a constrained equilibrium, in which cash holdings play a strategic role.

To concentrate on the constrained case, when solving the model, we first assume that the equilibrium is a constrained one and then we verify that the equilibrium conditions,  $C_1^* < \pi^*(2)$  and  $C_2^* < \pi^*(2)$ , are satisfied. In all parametrizations examined below, the equilibrium is such that firms are constrained in the second-stage duopoly and the strategic motive plays a role in firms' choices of cash holdings. We also verify that there are no additional, unconstrained, equilibria in which  $C_1^* > \pi^*(2)$  and  $C_2^* > \pi^*(2)$ .

In a constrained equilibrium, firm 1's second-stage investment threshold in the case in which both firms have succeeded in first-stage innovation equals

$$I_1^*(2, C_1, C_2, I_2(2)) = \frac{I_2(2)\pi^*(2) + (1 - I_2(2)) + C_1\alpha}{1 + \alpha}, \quad (13)$$

where  $I_2(2)$  is firm 2's chosen investment threshold. Similar expression holds for firm 2. Solving the resulting system of two equations results in the two equilibrium second-stage investment thresholds for the two firms:

$$I_1^*(2, C_1, C_2) = \frac{\pi^*(2) + \alpha + C_1\alpha(1 + \alpha) - C_2\alpha(1 - \pi^*(2))}{\pi^*(2)(2 - \pi^*(2)) + \alpha(2 + \alpha)}, \quad (14)$$

for firm 1 and a similar expression for firm 2.

In the case of  $N = 2$  and under the additional assumptions outlined above, the first-stage value of

firm 1 in Eq. (9) becomes

$$\begin{aligned}
V_1 = & - \left( C_1/r - \ln \left( (1 - p_i)^{\frac{1}{\alpha}} \right) \right) \\
& + \frac{1}{R} p_1 \left\{ p_2 \left[ \left( I_2^*(2, C_1, C_2) \pi^*(2) + 1 - I_2^*(2, C_1, C_2) + C_1 - \frac{I_1^*(2, C_1, C_2)}{2} \right) I_1^*(2, C_1, C_2) \right. \right. \\
& \left. \left. + C_1(1 - I_1^*(2, C_1, C_2)) + \left( C_1 - \frac{C_1 + I_1^*(2, C_1, C_2)}{2} \right) (1 + \alpha)(I_1^*(2, C_1, C_2) - C_1) \right] \right. \\
& + (1 - p_2) \left[ \left( \pi^*(1) + C_1 - \frac{I_1^*(1, C_1)}{2} \right) I_1^*(1, C_1) + C_1(1 - I_1^*(1, C_1)) \right. \\
& \left. \left. + \left( C_1 - \frac{C_1 + I_1^*(1, C_1)}{2} \right) (1 + \alpha)(I_1^*(1, C_1) - C_1) \right] \right\} + \frac{1}{R} (1 - p_1) C_1. \tag{15}
\end{aligned}$$

If firm 1 is successful in first-stage innovation and if it decides to implement it in the second stage, then it faces the possibility of duopolistic competition if firm 2 has also succeeded in its innovation and has decided to implement it in the second stage, while firm 1 would be a monopolist if firm 2 has not succeeded in innovation and/or it has decided not to implement it. In particular, it is possible to show that firm 1's value can be rewritten as

$$\begin{aligned}
V_1 = & - \left( C_1/r - \ln \left( (1 - p_i)^{\frac{1}{\alpha}} \right) \right) + \frac{1}{R} p_1 p_2 \mathbb{E}(\pi_1 | R \& D_2 = 1) \\
& + \frac{1}{R} p_1 (1 - p_2) \mathbb{E}(\pi_1 | R \& D_2 = 0) + \frac{1}{R} (1 - p_1) C_1, \tag{16}
\end{aligned}$$

where  $\mathbb{E}(\pi_1 | R \& D_2 = 1)$  and  $\mathbb{E}(\pi_1 | R \& D_2 = 0)$  are firm 1's expected second-stage values conditional on firm 2 succeeding and failing in first-stage innovation respectively, given by

$$\begin{aligned}
\mathbb{E}(\pi_1 | R \& D_2 = 0) &= \frac{-\alpha C_1^2}{2(1 + \alpha)} + \left( \frac{1 + 2\alpha}{1 + \alpha} \right) C_1 + \frac{1}{2(1 + \alpha)}, \\
\mathbb{E}(\pi_1 | R \& D_2 = 1) &= \Gamma_0 + \Gamma_1 C_1 + \Gamma_2 C_2 + \Gamma_3 C_1^2 + \Gamma_4 C_2^2 + \Gamma_5 C_1 C_2, \tag{17}
\end{aligned}$$

and

$$\begin{aligned}
\Gamma_0 &= \frac{1 + \alpha}{2} \phi_0^2, & \Gamma_1 &= (1 + \alpha) \phi_0 \phi_1 + 1, & \Gamma_2 &= (1 + \alpha) \phi_0 \phi_2, \\
\Gamma_3 &= \frac{(1 + \alpha)}{2} \phi_1^2 - \frac{\alpha}{2}, & \Gamma_4 &= \frac{(1 + \alpha)}{2} \phi_2^2, & \Gamma_5 &= (1 + \alpha) \phi_1 \phi_2, \\
\phi_0 &= \frac{1}{(1 + \alpha) + (1 - \pi^*(2))}, & \phi_1 &= \frac{(1 + \alpha)\alpha}{(1 + \alpha)^2 - (1 - \pi^*(2))^2}, & \phi_2 &= -\frac{(1 - \pi^*(2))\alpha}{(1 + \alpha)^2 - (1 - \pi^*(2))^2}, \tag{18}
\end{aligned}$$

and similarly for firm 2. Differentiating the value function of firm 1 in Eq. (16) with respect to  $C_1$

and  $p_1$  results in the following F.O.Cs:

$$-\frac{1}{r} + \frac{1}{R}p_1(1-p_2) \left( \frac{-\alpha C_1 + 1 + 2\alpha}{1 + \alpha} \right) + \frac{1}{R}p_1p_2(\Gamma_1 + 2\Gamma_3C_1 + \Gamma_5C_2) + \frac{1}{R}(1-p_1) = 0, \quad (19)$$

$$-\frac{1}{\delta(1-p_1)} + \frac{1}{R}p_2E(\pi_1|R\&D_2=1) + \frac{1}{R}(1-p_2)E(\pi_1|R\&D_2=0) - \frac{1}{R}C_1 = 0. \quad (20)$$

Solving the system of two equations in Eq. (19) and Eq. (20) results in firm 1's "reaction functions", i.e. optimal choices of the likelihood of innovation success and cash holdings as functions of firm 2's cash holdings and probability of successful innovation,  $p_1^*(C_2, p_2)$  and  $C_1^*(C_2, p_2)$ . Since similar F.O.C.s hold for firm 2, solving the resulting system of four equations in four unknowns leads to firms' equilibrium choices:  $p_1^*$ ,  $p_2^*$ ,  $C_1^*$ ,  $C_2^*$ . In the next subsection we analyze the shape of the reaction functions,  $p_1^*(C_2, p_2)$  and  $p_2^*(C_1, p_1)$ , and examine the comparative statics of the equilibrium quantities,  $p_1^*$ ,  $p_2^*$ ,  $C_1^*$ ,  $C_2^*$ , with respect to the cost of external financing,  $\alpha$ , the intensity of competition in the output market,  $\gamma$ , and innovation efficiency,  $\delta$ .

## 2.4. Results and comparative statics

### 2.4.1. Complementarity of R&D investments and cash holdings

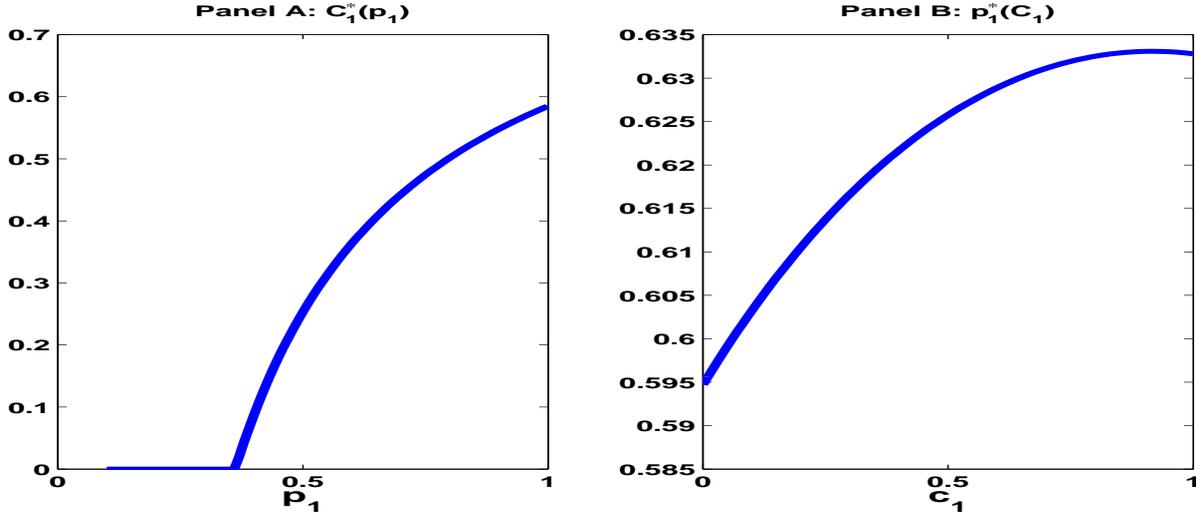
We begin by examining the (off-equilibrium) relations between the choices of investments in innovation and cash holdings by analyzing the effects of changing the likelihood of firm  $i$ 's innovation success,  $p_i$ , on its equilibrium cash holdings,  $C_i^*$ , and the effects of changing firm 1' cash holdings,  $C_1$ , on its equilibrium level of innovation and the resulting likelihood of innovation success,  $p_1^*$ , while holding the choices of firm 2 and the model's parameters constant. In particular, we assume the following parameter values:  $\alpha = 0.10$ ,  $r = 1$ ,  $R = 1.03$ ,  $\gamma = 0.50$ ,  $\delta = 7$ ,  $p_2 = 0.6210$ , and  $C_2 = 0.3829$ <sup>6</sup>. Panel A of Figure 2 presents  $C_1^*$  as a function of  $p_1$ , while Panel B presents  $p_1^*$  as a function of  $C_1$ .

Figure 2 illustrates the complementarity of  $p_i$  and  $C_i$ . The intuition for this complementarity is quite simple. Increasing the likelihood of successful innovation raises the probability of needing the

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<sup>6</sup>The values for  $p_2$  and  $C_2$  are the ones that would result in equilibrium.

Fig. 2. Complementarity of  $p_i$  and  $C_i$ .

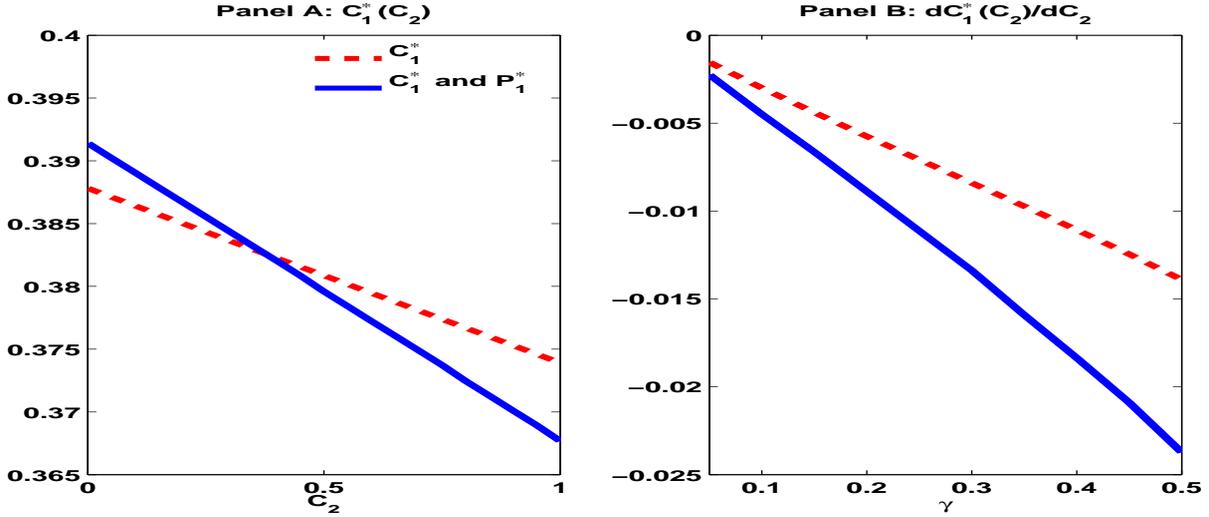


cash to exercise the investment option in the second stage. Thus, as illustrated in Panel A, optimal cash holdings are increasing in the level of investment in innovation. As follows from Eq. (6), cash holdings increase the likelihood of exercising the investment option in the second stage of the game by reducing the expected future financing costs. Thus, the marginal benefit of investing in innovation, which depends on the combination of the likelihood of innovation success and the probability of making the second-stage investment conditional on successful innovation, increases in cash holdings, leading to a positive effect of cash holdings on the optimal level of first-stage R&D investment, as illustrated in Panel B.

#### 2.4.2. Illustration of the strategic role of cash

In this subsection, we examine the strategic role of cash holdings. In particular, we examine the effects of changing firm 2's cash holdings,  $C_2$ , on firm 1's expected second-stage investment conditional on succeeding in first-stage innovation, on firm 1's equilibrium choice of cash holdings, and on firm 1's equilibrium likelihood of successful innovation. Panel A of Figure 3 presents the relation between  $C_2$

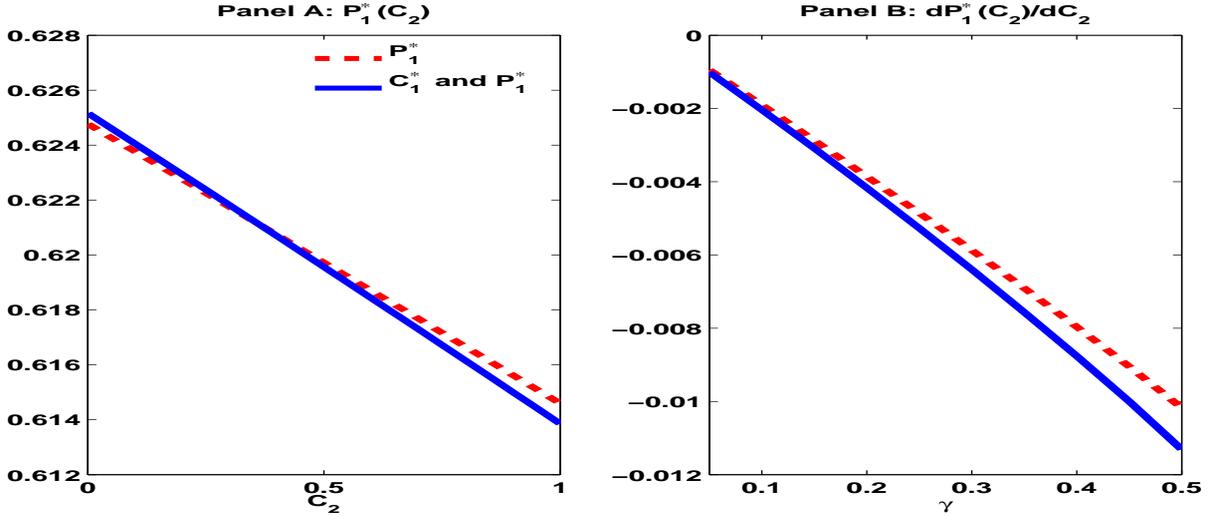
Fig. 3. Strategic role of cash I.



and  $C_1^*$ . The dashed line depicts the relation between  $C_2$  and  $C_1^*$  for the case in which the probabilities of innovation success,  $p_1$  and  $p_2$ , are constant at 0.6210 (which is the equilibrium value of firms' likelihoods of innovating successfully for the set of parameter values as in the previous subsection). Firm 2's cash holdings have a negative effect on firm 1's optimal level of cash holdings. The reason is that firm 2's higher cash reduces firm 1's investment threshold in a scenario in which both firms have succeeded in first-stage innovation. Thus, increasing  $C_2$  reduces the marginal benefit of holding cash for firm 1, resulting in lower equilibrium cash holdings,  $C_1^*$ .

The solid line in Panel A of Figure 3 depicts the case in which we relax the assumption of constant  $p_1$  and allow it to adjust optimally to changes in  $C_2$  (while still holding  $p_2$  constant at 0.6210 in order to focus on the strategic effect of cash holdings). The more negative slope of the solid line demonstrates that the negative relation between  $C_2$  and  $C_1^*$  is stronger when  $p_1$  is adjusted optimally to changes in  $C_2$  than when it is held constant. The reason is the complementarity between the choices of  $p_1$  and  $C_1$ , demonstrated in the previous subsection. A reduction in firm 1's optimal cash holdings results in a lower probability of second-stage investment by firm 1 (conditional on having succeeded in first-stage innovation), reducing the marginal benefit of investing in innovation in the first stage,

Fig. 4. Strategic role of cash II.

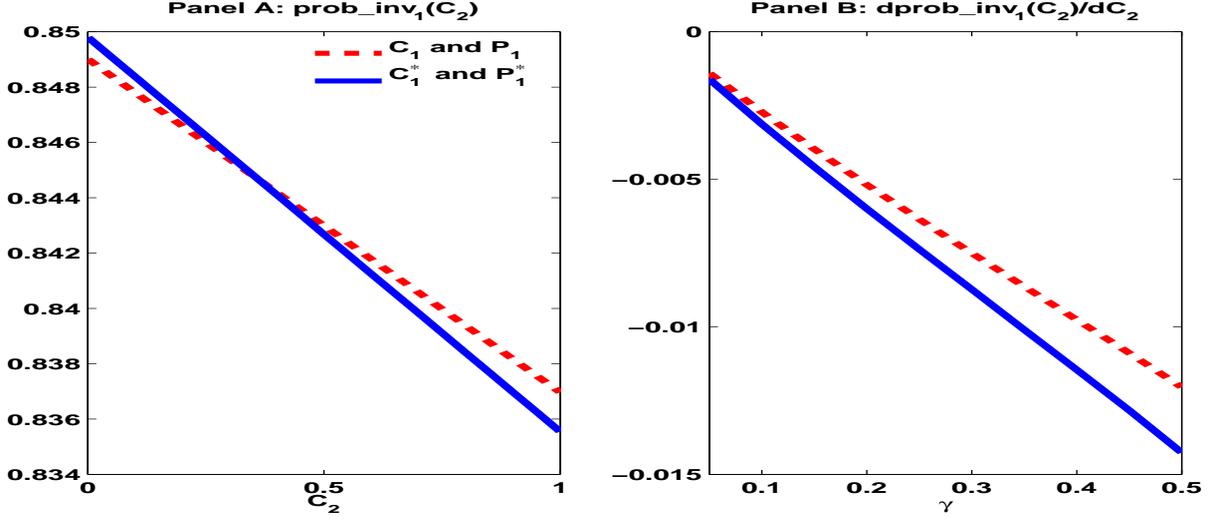


leading to lower  $p_1^*$ . Reduced  $p_1$ , associated with a lower likelihood of innovation success and the lower marginal benefit of cash, amplifies the reduction in firm 1's optimal cash holdings.

In Panel B of Figure 3, we investigate the effect of the intensity of output market competition on the strength of the relation between a firm's cash holdings and its rival's optimal cash holdings. In particular, for each  $\gamma$  ranging from 0.05 to 0.5, we compute the slope of the reaction function  $C_1^*(C_2)$  that equals  $C_1^*(1) - C_1^*(0)$ , for the case in which  $p_1$  is held constant at its equilibrium value (dashed line) and for the case in which  $p_1$  is allowed to adjust optimally to changes in  $C_1$  (solid line). This figure demonstrates that the strategic effect of a firm's cash holdings on its rival's optimal cash holdings is stronger the stronger the product substitutability, i.e. the more intense the competition in the output market.

In Panel A of Figure 4, we depict the relation between  $C_2$  and firm 1's optimal likelihood of innovation success,  $p_1^*$ , while holding firm 2's probability of success,  $p_2$ , at 0.6210. As in Figure 3, the dashed line depicts the case in which we hold  $C_1$  constant at its equilibrium value of 0.3829, while the solid line corresponds to the case in which we allow  $C_1$  to adjust optimally to changes in  $C_2$ . The model's parameters are the same as in the previous figures.

Fig. 5. Strategic role of cash III.



The direct effect of  $C_2$  on  $p_1^*$  is that of reducing the optimal likelihood of firm 1's second-stage investment conditional on first-stage success,  $I_1^*(2, C_1, C_2)$ , as follows from Eq. (14), which leads to a reduction in the marginal benefit of investing in innovation in the first stage. The negative effect of  $C_2$  on  $p_1^*$  is strengthened when we allow  $C_1^*$  to adjust optimally to changes in  $C_2$ . As shown in Figure 3, firm 1's optimal reaction to increased  $C_2$  is to reduce its own cash holdings,  $C_1$ , leading to further reduction in its likelihood of second-stage investment. The latter, in turn, leads to decreased marginal benefit of first-stage innovation and lower  $p_1^*$ .

In Panel B of Figure 4, we examine the relation between  $\gamma$  and the slope of  $p_1^*(C_2)$ ,  $p_1^*(1) - p_1^*(0)$ . The negative effect of a firm's rival's cash holdings on the firm's optimal level of investment in innovation is stronger the more intense the output market competition, more so in the case in which the firm's cash holdings are chosen optimally (solid line) than when they are held constant (dashed line).

Panel A of Figure 5 presents the relation between firm 2's cash holdings and firm 1's expected likelihood of second-stage investment conditional on having successfully innovated in the first stage,  $prob\_inv_1^* = p_2 I_1^*(2, C_1, C_2) + (1 - p_2) I_1^*(1, C_1)$ . The dashed line represents the case in which  $p_2$  is held constant at 0.6210 and  $C_1$  and  $p_1$  are held constant at 0.3829 and 0.6210 respectively.

The intuition for the negative relation between  $C_2$  and  $prob\_inv_1$  is as follows. Eq. (12) shows that firm 2's cash holdings do not affect firm 1's optimal investment threshold when the latter is operating as a monopolist in the second stage,  $I_1^*(1, C_1)$ . However, Eq. (14) shows that when both firms have succeeded in first-stage innovation, firm 1's optimal investment threshold and the resulting probability of second-stage investment,  $I_1^*(2, C_1, C_2)$ , are decreasing in  $C_2$ . Thus, holding  $p_2$  constant, firm 1's probability of investing in the second stage conditional on having succeeded in the first-stage innovation is decreasing in  $C_2$ .

The solid line in Panel A of Figure 5 depicts the case in which  $C_1$  and  $p_1$  are adjusted optimally to changes in  $C_2$  and  $p_2$ . It demonstrates that the negative relation between  $C_2$  and  $prob\_inv_1^*$  becomes stronger when we allow  $C_1$  and  $p_1$  to adjust optimally to changing  $C_2$  (while still holding  $p_2$  constant in order to isolate the strategic effect of cash holdings). Increasing  $C_2$  not only reduces firm 1's likelihood of second-stage innovation in a duopolistic scenario, but it also reduces firm 1's optimal cash holdings, as shown above, resulting in lower investment thresholds for firm 1 in the second-stage, amplifying the negative effect of a firm's cash holdings on its rival's likelihood of investment.

### 2.4.3. *Equilibrium cash holdings as a function of financing costs, competition intensity, and innovation efficiency*

The last subsection demonstrated that cash holdings affect investments in innovations and their implementation, and that cash holdings are not independent among firms innovating in related areas. These relations imply that firms may have incentives to choose their cash holdings strategically with the goal of affecting their rival's R&D and investment choices. In this section, we analyze the effects of financing costs,  $\alpha$ , innovation efficiency,  $\delta$ , and intensity of output market competition,  $\gamma$ , on firms' equilibrium choices of cash holdings. Since changes in  $\alpha$ ,  $\delta$  and  $\gamma$  affect firm values, given in Eq. (16), even when firms' cash holdings and innovation success probabilities are held constant, we examine normalized equilibrium cash holdings in the first stage of the game,  $\widetilde{C}_1^*$ . In particular, we normalize

the first-stage value of firm 1's cash holdings,  $\frac{C_1^*}{r}$ , by the firm's expected post-issue value:

$$\widetilde{C}_1^* = \frac{C_1^*/r}{\frac{1}{R}p_1p_2E(\pi_1|R\&D_2 = 1) + \frac{1}{R}p_1(1-p_2)E(\pi_1|R\&D_2 = 0) + \frac{1}{R}(1-p_1)C_1^*}, \quad (21)$$

and similarly for firm 2.<sup>7</sup> Because of symmetry, we only present the comparative statics of firm 1's normalized equilibrium cash holdings.

The top panel of Figure 6 presents the relation between the proportional cost of external funds,  $\alpha$ , and equilibrium normalized cash holdings. We let  $\alpha$  vary between 0.07 and 0.15. The other parameters take the following values:  $r = 1$ ,  $R = 1.03$ ,  $\gamma = 0.5$ ,  $\delta = 7$ . The solid black curve depicts the cash-to-value ratio defined in Eq. (21). The firm chooses its cash holdings without knowing whether its rival would succeed in its innovation. Therefore, intuitively, the firm's chosen cash holdings are a weighted average of the optimal cash holdings conditional on its rival successfully innovating and the optimal cash holdings conditional on the rival failing to innovate.

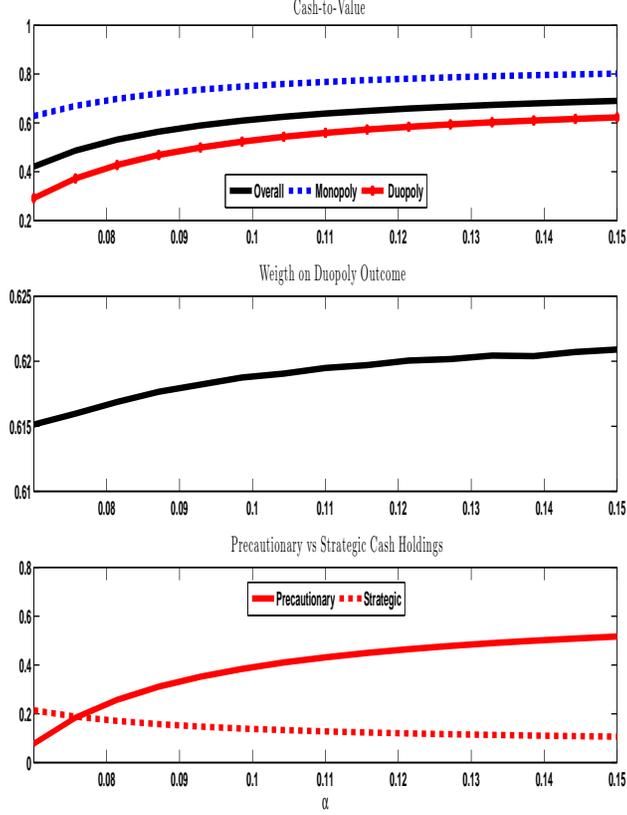
The remaining two curves in the top panel of Figure 6 are the result of a decomposition of optimal cash holdings into these two components. The solid red curve depicts the firm's optimal cash-to-value ratio conditional on the firm's rival being successful in innovation (the duopolistic scenario henceforth). The dashed curve represents the firm's optimal cash-to-value ratio conditional on its rival failing to innovate (the monopolistic scenario hereafter). The overall cash holdings (the solid black curve) are the weighted average of the conditional optimal cash holdings in the two scenarios (the other two curves).

The weights on the two scenarios are determined as follows. We first find firm 1's optimal cash holdings while assuming that firm 2 has succeeded in its innovation by solving firm 1's F.O.C. with respect to  $C_1$ , given in Eq. (19) and Eq. (20), while setting firm 2's probability of success,  $p_2$ , to one.

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<sup>7</sup>In the empirical literature examining the determinants of cash holdings (e.g., Opler, Pinkowitz, Stulz and Williamson (1999) Almeida and Campello (2004), and Bates, Kahle and Stulz (2009)), cash holdings are typically normalized by book assets. Book assets are meaningless in the first stage of the game in our model, hence the normalization by the firm's post-issue market value.

**Fig. 6.** Cash Holdings and the Costs of External Financing



Firm 1's resulting conditional optimal cash holdings are

$$C_1^*(p_1, C_2, R \& D_2 = 1) = \frac{-\frac{R}{r} + (1 - p_1) + (\Gamma_1 + \Gamma_5 C_2)p_1}{-2\Gamma_3 p_1}, \quad (22)$$

where  $\Gamma_1$ ,  $\Gamma_3$ , and  $\Gamma_5$  are given in Eq. (18). We then solve the same F.O.C. with respect to  $C_1$  while assuming that firm 2 would fail to innovate, i.e. setting its probability of innovation success,  $p_2$ , to zero. Firm 1's resulting optimal cash conditional on firm 2's failure is

$$C_1^*(p_1, R \& D_2 = 1) = \frac{-\frac{R}{r} + (1 - p_1) + \frac{1+2\alpha}{1+\alpha}p_1}{\frac{\alpha}{1+\alpha}p_1}. \quad (23)$$

Finally, we solve the same F.O.C. with respect to  $C_1$  without conditioning on firm 2's innovation success and express the resulting unconditional equilibrium cash holdings,  $C_1^*(p_1, C_2)$ , as a function of conditional equilibrium cash holdings  $C_1^*(p_1, C_2, R \& D_2 = 1)$  and  $C_1^*(p_1, R \& D_2 = 1)$  in Eq. (22) and

Eq. (23) respectively:

$$C_1^*(p_1, C_2) = w_{R\&D_2=1} C_1^*(p_1, C_2, R\&D_2 = 1) + w_{R\&D_2=0} C_1^*(p_1, R\&D_2 = 0),$$

where the weights on the duopolistic and monopolistic outcomes,  $w_{R\&D_2=1}$  and  $w_{R\&D_2=0}$  respectively, are given by

$$\begin{aligned} w_{R\&D_2=1} &= \frac{-2\Gamma_3 p_2}{\frac{\alpha}{1+\alpha}(1-p_2) - 2\Gamma_3 p_2}, \\ w_{R\&D_2=0} &= \frac{\frac{\alpha}{1+\alpha}(1-p_2)}{\frac{\alpha}{1+\alpha}(1-p_2) - 2\Gamma_3 p_2}. \end{aligned} \quad (24)$$

The middle panel of Figure 6 presents the weight on the duopolistic scenario,  $w_{R\&D_2=1}$ , evaluated at equilibrium  $p_1^*$ ,  $p_2^*$ , and  $C_2^*$ .

While in the monopolistic scenario the only motive to hold cash is precautionary, in the duopolistic scenario there are two reasons for holding cash: precautionary and strategic. The bottom panel of Figure 6 presents the breakdown of the optimal cash holdings in the duopolistic scenario, given in Eq. (22) as the precautionary and strategic components. The solid line presents the conditional precautionary cash holdings, while the dashed line presents the conditional strategic cash holdings. Precautionary cash holdings are obtained by solving the F.O.C. of firm 1 conditional on firm 2 failing to innovate, given in Eq. (23), while using the duopoly profit,  $\pi^*(2) = \frac{\mu^2(2-\gamma^2)}{(4+\gamma-\gamma^2)^2}$ , as the firm's third-period profit, as opposed to the monopoly profit,  $\pi^*(2) = 1$ , and evaluating the solution at equilibrium  $p_1^*$  and  $C_2^*$  and at  $p_2 = 0$ . Strategic cash holdings are the difference between the optimal conditional cash holdings under the duopolistic scenario and the optimal precautionary cash holdings under that scenario.

As is evident from the top panel of Figure 6, the cash-to-value ratio is monotonically increasing in the cost of external financing. This is quite intuitive. The precautionary savings motive becomes stronger as  $\alpha$  increases, since the more expensive is access to external funds, the more likely the firm is to reject the implementation of its innovation because of prohibitively high financing costs. Precautionary savings are increasing both in the monopolistic scenario, as follows from the increasing

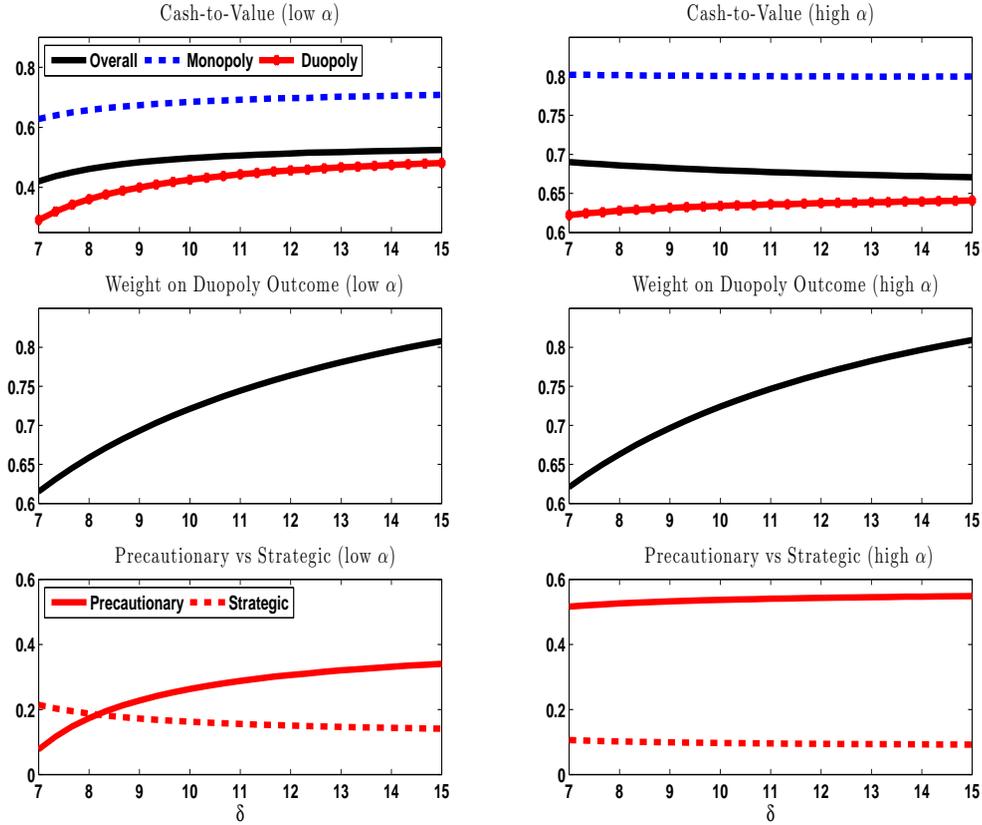
dashed blue line in the top panel, and in the duopolistic scenario, as follows from the solid line in the bottom panel.

Notably, strategic cash holdings are decreasing in the cost of external funds, as follows from the dashed line in the bottom panel of Figure 6. The reason is twofold. First, as follows from the optimal equilibrium second-stage investment threshold in Eq. (14), the strategic effect of  $C_2$  on  $I_1^*(2, C_1, C_2)$  (and, similarly, the effect of  $C_1$  on  $I_2^*(2, C_1, C_2)$ ) is decreasing in  $\alpha$ . Second, it follows from firm 1's F.O.C. with respect to  $C_1$ , given in Eq. (19), that the strength of the effect of  $C_2$  on  $C_1^*$  (and, similarly, the effect of  $C_1$  on  $C_2^*$ ) is decreasing in  $\alpha$ .  $C_2^*$ , in turn, is complementary with  $p_2^*$ , as demonstrated in the previous subsection. The result is the diminishing effect of  $C_1$  on firm 2's investment in innovation and the resulting likelihood of innovation success,  $p_2^*$ . These two negative effects of  $\alpha$  on the firms' ability to affect their rivals' first-stage and second-stage investments lead to a negative relation between the cost of external financing and strategic cash holdings.

We proceed to examining the relation between innovation efficiency,  $\delta$ , and the equilibrium cash-to-value ratio. Figure 7 depicts the relation between  $\delta$  and  $\widetilde{C}_1^*$  for two values of external financing costs:  $\alpha = 0.07$  in the left panels ("low  $\alpha$ " henceforth) and  $\alpha = 0.15$  in the right panels ("high  $\alpha$ " hereafter). The rest of the parameters take the same values as in Figure 6. Both the left and right panels of Figure 7 have the same meanings and were derived in the same way as in Figure 6.

When the cost of external financing is low, the equilibrium cash-to-value ratio is increasing in innovation efficiency, as follows from the top left panel of Figure 7. Both the optimal cash holdings conditional on the monopolistic outcome and those conditional on the duopolistic outcome are increasing in  $\delta$ . The reason is that increasing  $\delta$  raises the marginal benefit of investing in innovation and the equilibrium likelihood of innovation success,  $p_1^*$ . Higher  $p_1^*$ , in turn, raises optimal cash holdings in both scenarios because of the complementarity between  $p_1$  and  $C_1$ . This positive effect of  $\delta$  on the equilibrium cash-to-value ratios in both the duopolistic and monopolistic scenarios is mitigated by the fact that the weight on the duopolistic scenario,  $w_{R\&D_2=1}$ , in which the optimal cash holdings are

Fig. 7. Cash Holdings and R&D Efficiency



lower than those in the monopolistic case, is increasing in  $\delta$ . In other words, because an increase in  $\delta$  is associated with an increase in both  $p_1^*$  and  $p_2^*$ , the likelihood of the duopolistic outcome is increasing in  $\delta$ .

When the cost of external financing is high, the equilibrium cash-to-value ratio is decreasing in  $\delta$ , as follows from the solid black curve in the top right panel of Figure 7. The reason is that the (positive) slopes of the relations between conditional cash holdings and  $\delta$  in the duopolistic and monopolistic scenarios (represented by the solid red and dashed blue curves, respectively) are relatively flat. Conditional cash holdings are relatively insensitive to  $\delta$  because even when  $\delta$  is low, firms choose to have high cash holdings. The reason is that internal cash is the dominant source of financing successful innovation when external funds are expensive, as in the right panels of 7. Although the

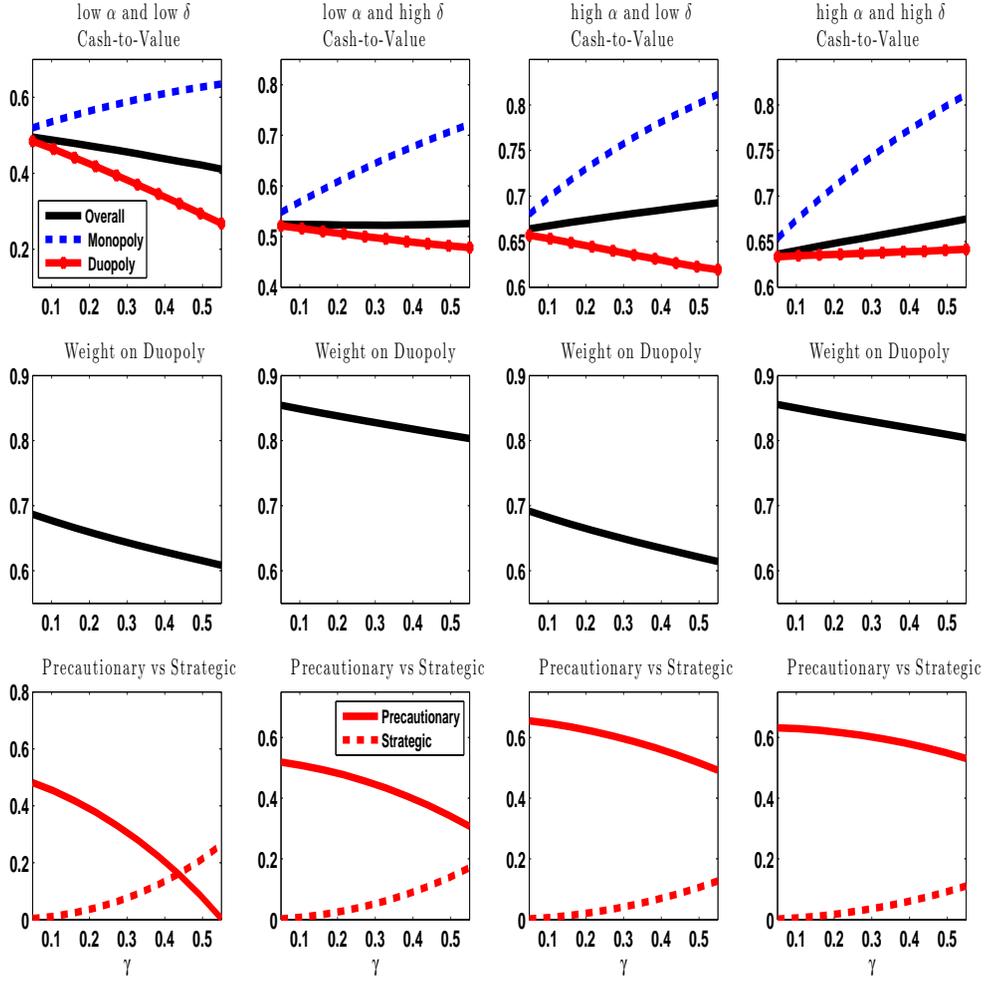
conditional cash holdings are increasing in  $\delta$ , the weighted average cash holdings are decreasing in  $\delta$  because the weight on the duopolistic scenario, in which optimal cash holdings are lower, is increasing in  $\delta$ , and this effect dominates the positive effect of  $\delta$  on conditional cash holdings.

Strategic cash holdings are decreasing in  $\delta$ , as evident from the two bottom panels. The reason is that the extent of complementarity between  $p_1$  and  $C_1$  (and, similarly, between  $p_2$  and  $C_2$ ) is decreasing in  $\delta$ , as follows from the F.O.C. in Eq. (20). The strategic effect of  $C_1$  on  $C_2^*$  does not depend on  $\delta$ . Thus, when  $\delta$  increases, a given decrease in firm 2's cash holdings due to an increase in firm 1's cash holdings leads to a lower change in firm 2's investment in innovation. This, in turn, reduces the strategic benefit of holding cash and equilibrium-strategic cash holdings.

Next, we examine the relation between the intensity of output market competition,  $\gamma$ , and equilibrium cash-to-value ratios. Figure 8 presents the relation between  $\gamma$  and  $\widetilde{C}_1^*$  for four combinations of the cost of external financing and innovation efficiency. In particular, the external financing cost,  $\alpha$ , takes the value of 0.07 in the leftmost and second panels (the “low  $\alpha$ ” case) and it takes the value of 0.15 in the third and the rightmost panels (the “high  $\alpha$ ” case). The innovation efficiency parameter,  $\delta$ , takes the value of 7 in the leftmost and third panels (the “low  $\delta$ ” case) and the value of 15 in the second and rightmost panels (the “high  $\delta$ ” case). We let the competition intensity parameter vary from 0.05 to 0.55. The rest of the parameters take the same values as in Figures 6 and 7. The three panels in all four scenarios depicted in Figure 8 have the same meanings and were derived in the same way as in Figures 6 and 7.

The most important conclusion from Figure 8 is that the equilibrium cash-to-value ratios are increasing in the intensity of competition for all combinations of  $\alpha$  and  $\delta$  except for when both  $\alpha$  and  $\delta$  take low values. The intuition is as follows. As in Figures 6 and 7, the equilibrium-unconditional cash holdings, represented by the solid black curves in the top panels of Figure 8, equal the weighted average of optimal cash holdings conditional on the rival firm succeeding in its innovation (the duopolistic case) and optimal cash holdings conditional on the rival firm's failure (the monopolistic case), depicted by

**Fig. 8.** Cash Holdings and Product Market Competition



the solid red curves and dashed blue curves, respectively.

The optimal cash-to-value ratio in the monopolistic scenario increases in  $\gamma$  for all sets of parameter values. The reason is that the equilibrium cash holdings,  $C_1^*$ , do not depend on  $\gamma$  in the monopolistic scenario, while the expected firm value is decreasing in  $\gamma$  because  $\gamma$  impacts the expected firm value in the duopolistic scenario negatively, leading to the positive relation between the normalized cash holdings,  $\widetilde{C}_1^*$ , and  $\gamma$  in the monopolistic case.

The effects of  $\gamma$  on the equilibrium cash holdings in the duopolistic case, represented by the solid red curve in the top panels of Figure 8, are somewhat more subtle. On one hand,  $\gamma$  increases the

strategic benefit of holding cash, as illustrated by the dashed red lines in the lower panels, since the strengths of the effects of the firm's cash holdings on its rival's optimal first-stage investment in innovation development and second-stage investment in innovation implementation are increasing in  $\gamma$ . On the other hand,  $\gamma$  reduces the expected firm values and the resulting marginal benefit of investment in innovation, which leads, in turn, to lower optimal investment in innovation and lower marginal benefit of holding cash, as illustrated by the decreasing solid curves in the lower panels of Figure 8.

The overall effect of competition intensity on equilibrium-unconditional normalized cash holdings depends on the relative strengths of the two effects of  $\gamma$  on the optimal cash holdings in the duopolistic scenario discussed above. The negative effect of  $\gamma$  on the precautionary savings motive is the strongest in the low  $\alpha$ -low  $\delta$  case. In other words, the slope of the solid curve in the leftmost bottom panel is steeper than in the rest of the bottom panels. Both low  $\alpha$  and low  $\delta$  contribute to this. When external funds are cheap, a decrease in the expected firm value in the duopolistic scenario caused by increased  $\gamma$  has a larger negative effect on optimal cash holdings because the marginal benefit of cash holdings is relatively low to begin with (i.e. even when  $\gamma$  is low) and further reduction in expected firm value, driven by the decrease in  $\gamma$ , makes holding cash even less attractive. When  $\delta$  is low, the equilibrium investment in innovation is low as well, and the likelihood of failing in innovation is high, making cash holdings relatively unattractive. In such a situation, an increase in  $\gamma$  makes cash holdings even less attractive.

The result of this trade-off is that the negative effect of  $\gamma$  on optimal precautionary savings in the duopolistic scenario outweighs the positive effects of  $\gamma$  on equilibrium cash holdings in the monopolistic scenario and on strategic cash holdings in the duopolistic scenario, leading to a negative relation between the intensity of competition and normalized cash holdings only when both the cost of external financing and innovation efficiency are low. In all other cases, the positive effects of  $\gamma$  on the equilibrium cash holdings in the monopolistic case and on the strategic cash holdings in the duopolistic case

outweigh the negative effect of  $\gamma$  on the precautionary savings in the duopolistic scenario, leading to the positive relation between the intensity of competition and cash-to-value ratios for all other combinations of the cost of external financing and innovation efficiency.

### 2.5. *N*-firm case solution and comparative statics

In this subsection, we present a numerical solution of the general case in which  $N$  firms compete in innovation. In what follows, we focus on a symmetric equilibrium in which all firms choose identical  $p_i^*$  and  $C_i^*$  in equilibrium. In particular, we first determine firms' optimal second-stage investment thresholds for the case of  $n$  firms that have succeeded in first-stage innovation, while assuming that cash holdings chosen in the first stage by all firms other than firm  $i$ , are identical,  $C_j \equiv C_{-i} \forall j \neq i$ , but not necessarily equal to the cash holdings of firm  $i$ , for various combinations of  $C_i$  and  $C_{-i}$ . Then, in the first stage, we determine optimal cash holdings and the likelihood of innovation success of firm  $i$ ,  $C_i^*(C_{-i}, p_{-i})$  and  $p_i^*(C_{-i}, p_{-i})$ , for various possible values of  $C_{-i}$  and  $p_{-i}$ . A symmetric equilibrium occurs when  $C_i^*(C_{-i}, p_{-i}) = C_{-i}$  and  $p_i^*(C_{-i}, p_{-i}) = p_{-i}$ . Because of symmetry,  $C_{-i}$  and  $p_{-i}$  also constitute equilibrium choices of firm  $i$ 's rivals, leading to a symmetric equilibrium in which the chosen cash holdings are identical across all firms, as are the chosen likelihoods of innovation success.

Assuming that all  $n - 1$  firms that have succeeded in innovation other than firm  $i$  have identical cash holdings, firm  $i$ 's constrained and unconstrained investment thresholds in Eq. (6) and Eq. (7) can be rewritten as follows:

$$I_i^*(n, \text{Constrained}) = \frac{\sum_{k=0}^{n-1} \frac{(n-1)!}{k!(n-1-k)!} I_{-i}^*(n, C_i, C_{-i})^k (1 - I_{-i}^*(n, C_i, C_{-i}))^{n-k-1} \pi^*(k+1) + C_i \alpha}{1 + \alpha}, \quad (25)$$

$$I_i^*(n, \text{Unconstrained}) = \sum_{k=0}^{n-1} \frac{(n-1)!}{k!(n-1-k)!} I_{-i}^*(n, C_i, C_{-i})^k (1 - I_{-i}^*(n, C_i, C_{-i}))^{n-k-1} \pi^*(k+1). \quad (26)$$

Similarly, assuming symmetry across all firms other than  $i$ , the investment thresholds of a representa-

tive firm  $j \neq i$  can be written as

$$I_{-i}^*(n, \text{Constrained}) = \left( \sum_{k=0}^{n-2} \frac{(n-2)!}{k!(n-2-k)!} I_{-i}^*(n, C_i, C_{-i})^k (1 - I_{-i}^*(n, C_i, C_{-i}))^{n-k-2} (I_i^*(n, C_i, C_{-i}) \pi^*(k+2) \right. \\ \left. + (1 - I_i^*(n, C_i, C_{-i})) \pi^*(k+1) \right) + C_{-i} \alpha / (1 + \alpha), \quad (27)$$

$$I_{-i}^*(n, \text{Unconstrained}) = \sum_{k=0}^{n-2} \frac{(n-2)!}{k!(n-2-k)!} I_{-i}^*(n, C_i, C_{-i})^k (1 - I_{-i}^*(n, C_i, C_{-i}))^{n-k-2} (I_i^*(n, C_i, C_{-i}) \pi^*(k+2) \\ + (1 - I_i^*(n, C_i, C_{-i})) \pi^*(k+1)). \quad (28)$$

Solving the system of two equations in Eq. (25)-(26) and Eq. (27)-(28) with respect to  $I_i^*(n, C_i, C_{-i})$  and  $I_{-i}^*(n, C_i, C_{-i})$  for various combinations of  $C_i$  and  $C_{-i}$  results in equilibrium second-stage investment thresholds of firm  $i$  and its  $n-1$  rivals conditional on  $n$  firms succeeding in innovation.

We then plug the equilibrium investment thresholds obtained above into firm  $i$ 's value function in Eq. (9), in which firm  $i$ 's expected third-stage payoff conditional on  $n$  firms having succeeded in first-stage R&D is given by

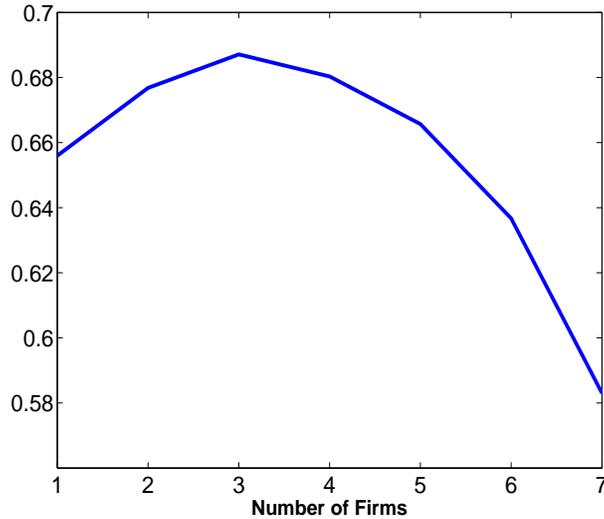
$$\mathbb{E}_{i,n}(\pi^*(n)) = \sum_{k=0}^{n-1} \frac{(n-1)!}{k!(n-1-k)!} I_{-i}^*(n, C_i, C_{-i})^k (1 - I_{-i}^*(n, C_i, C_{-i}))^{n-k-1} \pi^*(k+1), \quad (29)$$

and we maximize this value function with respect to  $C_i$  and  $p_i$ , resulting in firm  $i$ 's equilibrium choices of cash holdings and likelihood of R&D success conditional on  $C_{-i}$  and  $p_{-i}$ ,  $C_i^*(C_{-i}, p_{-i})$  and  $p_i^*(C_{-i}, p_{-i})$ . As mentioned above, the combination of  $C_{-i}$  and  $p_{-i}$  that satisfy  $C_i^*(C_{-i}, p_{-i}) = C_{-i}$  and  $p_i^*(C_{-i}, p_{-i}) = p_{-i}$  constitutes a symmetric equilibrium, whose comparative statics with respect to the number of firms in the industry,  $N$ , we examine next.

Figure 9 presents the relation between (symmetric) firms' equilibrium normalized cash holdings,  $\widetilde{C}_1^*$ , and the number of firms in the industry,  $N$ , for the following set of parameter values:  $\alpha = 0.1$ ,  $r = 1$ ,  $R = 1.03$ ,  $\gamma = 0.5$ ,  $\delta = 10$ .

Normalized cash holdings exhibit an inverse U-shaped relation with the number of firms. The intuition is as follows. When the number of firms is low, if a firm succeeds in first-stage innovation, it is relatively likely to be the only successful firm. In such a scenario there is no strategic motive for holding cash, and cash holdings serve only a precautionary role. As the number of firms increases,

**Fig. 9.** Cash Holdings and Number of Rivals



the one-firm scenario in the second stage becomes increasingly unlikely, raising the likelihood of cash being useful for strategic reasons (i.e. for reducing the likelihood of a firm's rivals' implementing their innovations in the second stage of the game), and increasing the overall equilibrium cash holdings relative to firm values. This explains the increasing part of the relation between  $\widetilde{C}_1^*$  and  $N$ . However, as the number of firms keeps growing, the likelihood of facing multiple rivals in the second stage of the game increases. The strategic role of cash in reducing rivals' investment thresholds weakens as the number of rivals rises (it is the highest when a firm faces one second-stage rival). Thus, when  $N$  is sufficiently high, the equilibrium-normalized cash holdings start exhibiting a negative relation with the number of firms, resulting in the overall hump-shaped relation between  $\widetilde{C}_1^*$  and  $N$ . This hump-shaped relation is more pronounced for the case of relatively high  $\gamma$  (the solid line) because the strategic effects of cash holdings are increasing in  $\gamma$ .

### 2.6. Summary of empirical predictions

The comparative statics discussed in the previous two subsections concern the effects of financing costs, innovation efficiency, intensity of output market competition (i.e. product substitutability), and

industry structure (i.e. the number of rival firms) on firms' equilibrium choices of cash holdings. These predictions follow from the comparative statics in Figures 6-9. In what follows "cash holdings" refer to equilibrium-normalized cash holdings in the model.

**Prediction 1.** *Firms' cash holdings are expected to be increasing in the cost of obtaining external financing.*

**Prediction 2.** *Cash holdings of firms facing relatively low costs of external financing are expected to be increasing in innovation efficiency. Cash holdings of firms facing relatively high costs of external financing are expected to be decreasing in innovation efficiency*

**Prediction 3.** *Firms' cash holdings are expected to be increasing in the intensity of product market competition except for firms facing relatively low costs of external financing and having relatively low innovation efficiency.*

**Prediction 4.** *Firms' cash holdings are expected to exhibit a hump-shaped relation with the number of firms' innovating in their industry.*

In the next section, we test these predictions empirically using data on patent grants and citations, which we use in order to identify a sample of firms that compete in innovation and to develop proxies for innovation efficiency, intensity of output market competition, and industry structure.

### 3. Empirical tests

#### 3.1. *Data, empirical specification, variables, and summary statistics*

In this section, we describe the data used in the empirical analysis, the empirical specification that we use to test the model's predictions, and the summary statistics produced by our variables.

### 3.1.1. *Data sources*

We employ three data sources in our empirical tests. The first is the NBER Patent Citations Data Project<sup>8</sup>, which we use to construct a sample of innovating firms, to identify industries in which firms innovate, and to develop measures of innovation efficiency. The second is the CRSP/Compustat Merged Database, which provides information on various accounting variables that we employ in the analysis. The third data source, used to construct a proxy for firms' financing costs based on analyst coverage, is the Institutional Broker Estimates System (I/B/E/S).

The NBER Patent Data Project contains data on all utility patents granted by the U.S. Patent and Trademark Office between 1976 and 2006. For each patent, the dataset contains an assigned GVKEY code, which we use to match patent data to Compustat, the date when the patent was granted, the patent's technology field (class) defined according to the International Patent Classification system, and the number of times the patent has been cited. Naturally, our analysis includes only firms that have filed at least one utility patent.

In our empirical analysis, following Bena and Garlappi (2011), we treat each of the 324 technology classes as a separate industry. In what follows we use the terms "class" and "industry" interchangeably. Each year we aggregate patent grants by firm and assign a firm to the single patent class in which it obtained the most patents during that year. Since we are interested in firms' strategic choices of cash holdings, we concentrate on patent classes in which at least two firms were granted patents in a given year. Restrictions on Compustat data availability led to a final sample of 27,864 firm-years with patent grants.

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<sup>8</sup><https://sites.google.com/site/patentdataproyect/Home>

### 3.1.2. Empirical specification

The empirical predictions summarized in the previous section concern determinants of firms' cash holdings, in particular the cost of external financing, innovation efficiency, intensity of competition, and industry structure. Our empirical specification relates proxies for these factors to normalized cash holdings, while incorporating the fact that the signs of the relations between cash holdings and some of their determinants may differ across various subsamples of firms.

Our basic empirical specification takes the following form:

$$Cash_{(i,t) \in k} = \beta_0 + \beta_1 \tilde{\alpha}_{i,t} + \beta_2 \tilde{\delta}_{i,t} + \beta_3 \tilde{\gamma}_{k,t} + \beta_4 \overrightarrow{X}_{i,t} + \varepsilon_{i,t}, \quad (30)$$

where  $Cash_{(i,t) \in k}$  is the measure of the normalized time- $t$  cash holdings of firm  $i$ , whose main patent class in year  $t$  is  $k$  (i.e. class  $k$  is the one in which firm  $i$  filed the most patents in year  $t$ ),  $\tilde{\alpha}_{i,t}$  is a proxy for firm  $i$ 's cost of external financing,  $\tilde{\delta}_{i,t}$  is a measure of firm  $i$ 's innovation efficiency,  $\tilde{\gamma}_{k,t}$  is a measure of competition intensity in class  $k$ .  $\overrightarrow{X}_{i,t}$  represents a vector of control variables similar to those used in past empirical studies of cash holdings (e.g., Opler, Pinkowitz, Stulz and Williamson (1999) and Han and Qiu (2007), and Bates, Kahle and Stulz (2009)) and discussed in detail below.

While our model is capable of explaining the empirical finding of a temporal increase in firms' cash holdings, which is concentrated mostly within innovative firms, the model's specific empirical predictions concern mostly cross-sectional relations between the cost of external financing, innovation efficiency, intensity of competition, and industry structure on one side and firms' cash holdings on the other side. For that reason the regression in (30) is estimated using year fixed effects. In addition, as noted in Hall, Jaffe and Trajtenberg (2005), the data on patent citations is necessarily truncated, since many of the citations to patents in the NBER Patent Data Project will occur in the future. This problem may be more severe for relatively recent patent grants, although Bernstein (2011) and Akcigit and Kerr (2010) report that most citations happen within the first few years of patent grants. Estimating Eq. 30 with year fixed effects mitigates this problem. While estimating Eq. 30, we cluster standard errors at the patent class level.

3.1.3. *Measures of costs of external financing, innovation efficiency, intensity of competition, and industry structure*

In our model, cash is normalized by the firm's market value. However, to be consistent with past empirical studies on the determinants of cash holdings, we normalize cash holdings by the value of book assets and compute normalized cash holdings as the ratio of Compustat item CHE and item AT.<sup>9</sup>

A firm's cost of external financing is generally unobservable, making proxy variables necessary. One of the most important determinants of the cost of external funds relative to that of internally-generated funds is the degree of information asymmetry between the firm and the capital market (e.g. Leland and Pyle (1977) and Myers and Majluf (1984)). The reason is that moral hazard prevents the transfer of information between the firm and the capital market. Insufficient information lowers the market's assessment of the firm and of its projects and raises the firm's cost of external financing. The moral hazard problem is expected to be especially severe among innovating firms deriving large portions of their values from growth options. The cost of external financing is expected to increase monotonically in the extent of information asymmetry. Since there are no perfect proxies for the degree of asymmetric information, we use four different (imperfect) proxies.

Following the investment-cash flow sensitivity literature (e.g., Gilchrist and Himmelberg (1995) and Erickson and Whited (2000)) and the cash holdings literature (e.g., Han and Qiu (2007)), our first (inverse) measure of information asymmetry is firm size, measured as the logarithm of book assets,  $\tilde{\alpha}_{i,t}^1 = \log(\text{AT})$ , as larger firms are expected to face less severe information asymmetry than smaller ones.

Our second (inverse) measure of information asymmetry is the logarithm of firm age,  $\tilde{\alpha}_{i,t}^2 = \log(\text{AGE})$ , where firm  $i$ 's AGE in year  $t$  equals one plus the difference between  $t$  and the firm's founding year or

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<sup>9</sup>We repeat all the tests while using the ratio of cash to the sum of market value of equity and book value of debt,  $\frac{\text{CHE}}{\text{PRCC\_F} \times \text{CSHO} + \text{CEQ} + \text{PREF\_STOCK}}$ , as the dependent variable and find results similar to those obtained using the main specification.

These results are available upon request.

its incorporation year or the first year in which the firm appears in Compustat, in that order of availability. Older, more established firms are likely to be characterized by a lower degree of information asymmetry and lower costs of external financing than younger firms.

Following Fazzari, Hubbard and Petersen (1988), Cleary (1999), and Han and Qiu (2007) among others, our third (inverse) proxy for the cost of external financing is an indicator variable equalling one if the firm paid dividends or repurchased shares in a given year,  $\tilde{\alpha}_{i,t}^3 = 1$  if  $DV > 0$  or  $PRSTKC > 0$ , and  $\tilde{\alpha}_{i,t}^3 = 0$  otherwise. Finally, following Whited and Wu (2006), our fourth (inverse) proxy for the cost of external financing is the inverse of the number of unique analysts providing estimates of firm  $i$ 's annual earnings per share in year  $t$ ,  $\tilde{\alpha}_{i,t}^4 = \#Analysts$ , as analyst coverage reduces asymmetric information.<sup>10,11</sup>

Following Hall, Jaffe and Trajtenberg (2005), Schroth and Szalay (2010), and Hirshleifer, Hsu and Li (2010) among others, our measure of innovation efficiency is based on the number of citations that patents generate per dollar of R&D spending. In particular, for each firm-year, we compute the number of citations to firm's patents granted in that year and divide this measure by a measure of the firm's expenditures on R&D required to generate these patents. We use the number of citations to patents, as opposed to the number of patents, as a measure of R&D outcome, since Hall, Jaffe and Trajtenberg (2005) find that it is important to account for the "quality of innovation", measured by the number of citations per patent, as well as for the "quantity of innovation", measured by the number of patents per million dollar of R&D expenditure.

We follow Hall, Jaffe and Trajtenberg (2005) and proxy for the R&D expenditures required to provide patents that are granted in year  $t$  by the estimated "R&D stock" at the end of year  $t - 1$ . We

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<sup>10</sup>Replacing the number of analysts by the standard deviation of analyst forecasts, as in Diether, Malloy and Scherbina (2002) reduces the sample substantially, since it eliminates firms covered by fewer than two analysts, but leads to similar qualitative results.

<sup>11</sup>Another popular measure of financial constraints used in past literature is the availability of debt ratings (e.g., Gilchrist and Himmelberg (1995)). We do not use this measure in our tests, as debt of our sample firms is seldom rated.

use the perpetual inventory method to evaluate R&D stock:

$$R\&Dstock' = (1 - \theta)R\&Dstock + R\&Dex, \quad (31)$$

where  $R\&Dstock'$  and  $R\&Dstock$  are the stocks of R&D in two consecutive years,  $\theta$  is the rate of depreciation of R&D stock, and  $R\&Dex$  is R&D expenditure. Imposing a constant growth rate,  $\frac{R\&Dstock' - R\&Dstock}{R\&Dstock} = g$ , it follows from Eq. (31) that

$$R\&Dstock = \frac{R\&Dex}{g + \theta}. \quad (32)$$

To estimate the value of R&D stock, we begin by computing each firm's "initial"  $R\&Dstock$  in Eq. (32) in 1969, which is seven years prior to the beginning of our sample period, or the first year in which a firm appears in Compustat. We proxy for  $R\&Dex$  in Eq. (32) by R&D expenditures, Compustat item XRD in 1969. We then evaluate  $g$  as the mean growth rate of real R&D expenditures at the firm level in the seven years preceding the beginning of our sample period (i.e. years 1969-1975 or the first year in which a firm appears in Compustat). Finally, following Hall, Jaffe and Trajtenberg (2005), we use 15% as the rate of depreciation of R&D stock,  $\theta$ . After having estimated the initial R&D stock, we recursively estimate R&D stocks in all future years by depreciating existing stock by 15% each year and adding annual R&D expenditures<sup>12</sup>. Finally, we delete the first seven years of estimated R&D stocks and use estimated R&D stocks in all other years. Importantly, R&D stock estimates in years following the first seven are not very sensitive to the chosen value of initial R&D stock.

Our first measure of firm  $i$ 's innovation efficiency in year  $t$ ,  $\tilde{\delta}_{i,t}^1$ , is, thus, estimated as

$$\tilde{\delta}_{i,t}^1 = \log \left( \frac{\sum_{j \in (i,t)} CIT_{j,i,t}}{R\&Dstock_{i,t-1}} \right), \quad (33)$$

where  $CIT_{j,i,t}$  is the number of citations generated by patent  $j$  filed by firm  $i$  in year  $t$ , and  $R\&Dstock_{i,t-1}$  is firm  $i$ 's estimated R&D stock in year  $t - 1$ .

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<sup>12</sup>If there are one or two consecutive years of missing R&D expenditure data, we interpolate the missing values using a cubic polynomial. If a firm has missing observations that exceed two consecutive years after the first reported R&D value, we drop this firm from the sample.

While our measure of R&D efficiency in Eq. (33) is theoretically justified, many observations are lost due to discarding the first seven years for each firm and also due to gaps in reporting of R&D expenditures, which are magnified in the estimation of R&D stocks. Thus, in our alternative measure of innovation efficiency, citations to firm  $i$ ' patents granted in year  $t$  are normalized by year  $t - 1$ 's R&D expenditure:

$$\tilde{\delta}_{i,t}^2 = \log \left( \frac{\sum_{j \in (i,t)} CIT_{j,i,t}}{R\&D_{i,t-1}} \right). \quad (34)$$

Our measure of intensity of output market competition is based on the idea that competition intensity is increasing in product substitutability (e.g., Syverson (2004) and Goettler and Gordon (2011)). Substitutability is likely to be positively related to how focused firms' R&D activities are. For example, products of two firms that develop all of their patents in the same single patent class are likely to be more substitutable than products of two firms that are assigned to the same patent class but develop patents in many classes, with only a minority of the patents being in the "main" class to which both of them happen to belong. Thus, for each firm-year, we measure the proportion of citations to patents that are filed in a given class to the total citations to patents filed by that firm in that year. We then average these proportions across all firms assigned to main patent class  $k$  to obtain a class-wide measure of intensity of output market competition,  $\tilde{\gamma}_{k,t}$  for patent class  $k$  in year  $t$ :

$$\tilde{\gamma}_{k,t} = \frac{\sum_{(i,t) \in k} \left( \frac{\sum_{(j,i,t) \in k} CIT_{j,i,t}}{\sum_{j,i,t} CIT_{j,i,t}} \right)}{\#firms_{k,t}}, \quad (35)$$

where  $\#firms_{k,t}$  is the number of firms whose main patent class in year  $t$  is  $k$ .

Finally, we measure industry structure by the number of rivals, following e.g., Aoki (1991) and Spence (1984) among many others, in the context of competition in innovation. The number of firms in a given industry-year is proxied by the number of firms that have filed patents in that patent class during that year:  $\tilde{N}_{k,t} = \#firms_{k,t}$ .

### 3.1.4. Control variables in cash holdings regressions

We largely follow Han and Qiu (2007) and Bates, Kahle, Stulz and Williamson (2009) in the selection of control variables in Eq. (30). In particular, we control for investment opportunities, proxied by lagged market-to-book ratio,  $MB_{i,t-1}$ ; lagged net working capital,  $NWC_{i,t-1}$ , since net working capital can be considered a substitute for cash; internal cash flow,  $CF_{i,t}$ , since firms with higher cash flow are likely to require lower precautionary cash holdings; lagged net investment in PP&E,  $INV_{i,t-1}$ , since capital expenditures create assets that can be used as collateral, reducing the need for precautionary cash; lagged book leverage,  $LEV_{i,t-1}$ , both because firms may use cash to reduce leverage and because cash can serve as a hedge for highly levered firms; and cash flow volatility,  $CFVOL_{i,t}$ , which may increase the precautionary savings motive. In addition, we control for the firm's diversification,  $DIVER_{i,t}$ , because diversification reduces the precautionary savings motive.

$MB_{i,t-1}$  is computed as follows. We follow Davis, Fama and French (2000) and define book equity as stockholder equity (SEQ) plus balance sheet deferred taxes and investment tax credit (TXDITC, if available) minus the book value of preferred stock. Preferred stock is defined as PSTKRV or PSTKL or PSTK in this order of availability. If SEQ is missing, stockholder equity is defined as the book value of common equity (CEQ) plus the par value of preferred stock (PSTKL). If SEQ and CEQ are both missing, then stockholder equity is defined as total assets (AT) minus total liabilities (LT). Market equity is the fiscal-year-end share price (PRCC\_F) multiplied by the number of common shares outstanding (CSHO).  $NWC_{i,t-1}$  is computed as the difference between working capital (WCAP) and cash, normalized by lagged assets.  $CF_{i,t}$  is defined as net income before extraordinary items (IB) plus depreciation (DP), normalized by lagged book assets.  $INV_{i,t-1}$  is defined as the difference between investment in PP&E, CAPX, and sale of PP&E, SSPE (if available), normalized by lagged assets.  $LEV_{i,t-1}$  is the sum of long-term and short-term debt, DLTT and DLC, divided by book assets.  $CFVOL_{i,t}$  is computed as the standard deviation of firm  $i$ 's quarterly cash flows normalized by lagged book assets during the 16

quarters in years  $t - 4$  to  $t - 1$ .<sup>13</sup> Finally,  $DIVER_{i,t}$  equals to the number of classes in which firm  $i$  filed patents in year  $t$ .

### 3.1.5. Summary statistics

Table 1 presents summary statistics for cash holdings, measures of external financing costs, innovation efficiency, intensity of output market competition, and industry structure, and control variables used in the regressions below. In Table 1, as well as in the empirical analysis below, we winsorize all ratios not bounded by 0 and 1 at the first and 99<sup>th</sup> percentiles

Insert Table 1 here

The mean cash-to-assets ratio of a firm in our sample is 0.21, and the median cash-to-asset ratio is 0.11, slightly higher than the numbers in Opler, Pinkowitz, Stulz and Williamson (1999) and Almeida and Campello (2004). Given that ours is a sample of R&D-intensive firms, this is consistent with the evidence mentioned in the introduction that innovating firms tend to hold more cash on average. The mean (median) market-to-book ratio is 1.95 (1.23), which is somewhat higher than the mean and median market-to-book ratios of Compustat firms, consistent with firms in our sample deriving a relatively large part of their value from growth options. The mean (median) investment-to-asset ratio is 0.06 (0.05), which is consistent with e.g., Riddick and Whited (2009) and Whited (2006). The mean (median) book leverage is 0.2 (0.18), somewhat lower than typical in capital structure studies (e.g., Frank and Goyal (2009)) and consistent with the negative relation between growth options and optimal leverage (e.g., Smith and Watts (1992), Rajan and Zingales (1995), and Barclay, Morellec and Smith (2009)).

Firms in our sample vary quite widely with respect to their proxies for the degree of information

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<sup>13</sup>Using the coefficient of variation of cash flow, as in Han and Qiu (2007), provides similar results. We prefer not to normalize our measure of cash flow volatility by the absolute value of mean cash flow as in Han and Qiu (2007) because doing so is problematic in cases in which mean cash flow is close to zero.

asymmetry and expected costs of external financing. The average (median) firm in our sample has book assets worth \$M2,797 (\$M163) in 1982 dollars with large variation in firm size. Similarly, the average (median) firm in our sample is 37 (20) years old, while the oldest (youngest) firm is 232 (1) years old. 61% of the firms in our sample pay dividends or repurchase shares in any given year. The average (median) firm is followed by 3 (1) analysts, while the most widely-followed firm has 32 analysts covering it.

The average (median) number of patents that firms in our sample are granted annually is 28 (3). The distribution of patent grants is highly right-skewed and its standard deviation is large (125). The same is true for the distribution of citations: the mean (median) number of citations to patents filed by a firm in a given year is 238 (23) and the standard deviation of the number of citations is 1,129. The average (median) firm generates 2.6 (0.7) patent citations per 1 million dollar of R&D stock and 16 (3) citations per 1 million dollar previous-year R&D expenditures.

A typical firm files patents in multiple classes: the mean (median) number of classes in which firms are granted patents in a given year is 7 (2). However, the majority of patents are filed within one patent class: the average (median) proportion of patents filed in the “main” class is 0.71 (0.79). Finally, firms do not operate alone in their patent classes: the average (median) number of firms that file patents in a given patent class in a given year is 13 (7).

### *3.2. Determinants of cash holdings*

Our four empirical predictions concern the effects on cash holdings of the costs of external financing,  $\alpha$ , innovation efficiency,  $\delta$ , product market competition intensity,  $\gamma$ , and industry structure,  $N$ . In this section we test these predictions by examining the relation between proxies for  $\alpha$ ,  $\delta$ ,  $\gamma$ , and  $N$  and firms’ cash-to-assets ratios.

### 3.2.1. Tests of Prediction 1

We begin by analyzing the relation between firms' cash holdings and the proxies for the costs of external financing. Unlike the other model parameters, the relation between  $\alpha$  and normalized cash holdings is predicted to be monotonic for all possible values of other model parameters. Thus, to test Prediction 1, we estimate the regression in Eq. (30) within the full sample of innovating firms.

Insert Table 2 here

Table 2 has three panels. In the first panel we use our preferred measure of  $\delta$ , the logarithm of the ratio of the number of citations and R&D stock,  $\tilde{\delta}_{i,t}^1$ . However, for the reasons described above, estimates of R&D stock are missing for many firm-years. Therefore, in the second panel, we use our alternative measure of  $\delta$ , the ratio of citations to lagged R&D expenditures,  $\tilde{\delta}_{i,t}^2$ , increasing the number of observations by close to 40%. Finally, in the third panel we increase the number of observations by another 40% by omitting one of the control variables in Eq. (30), cash flow volatility, which is missing for many of our sample firms due to the requirement of availability of past quarterly cash flow data.

In each of the three panels in Table 2 we employ four specifications, corresponding to our four (inverse) measures of the costs of external financing: the logarithm of book assets, the logarithm of firm age, an indicator variable equalling one for dividend-paying or stock-repurchasing firms, and the number of analysts following a firm. The coefficients of interest, highlighted in bold, are those on the proxies for the costs of external financing. Importantly, these coefficients are negative and statistically significant at a 1% level in all twelve specifications, illustrating a statistically strong negative relation between firms' costs of external financing and their cash holdings.

Perhaps more importantly, these coefficients seem economically significant. For example, increasing the logarithm of firm size from the first quartile to the third quartile (3.62 and 6.86 respectively) reduces cash holdings by 6.8 - 10.4 percentage points *ceteris paribus*. These estimates are very sizable when compared with the mean cash-to-asset ratio of 0.2 in our sample. Similarly, moving from the first to

the third quartile of the logarithm of firm age (2.30 and 4.04 respectively) decreases cash holdings by 6.4 - 7.1 percentage points. Dividend-paying and repurchasing firms typically have 5 - 7.5 percentage points lower cash holdings than firms that do not distribute cash to shareholders. Finally, the cash holdings of a firm followed by four analysts are about five percentage points lower than those of a similar firm that does not have analyst coverage. These findings are consistent with the documented negative relation between cash holdings and proxies for financial constraints in e.g., Opler, Pinkowitz, Stulz and Williamson (1999), Harford (1999), and Faulkender and Wang (2006).

Since the signs of the predicted relations between cash holdings on one side and measures of innovation efficiency,  $\delta$ , and competition intensity,  $\gamma$ , on the other side, depend on the level of external financing costs, the coefficients on citations-to-R&D and proportions of citations to patents filed in the main patent class are not informative in the full sample and will be re-examined in a subsample analysis below. The coefficients on the control variables are generally consistent with past studies and intuition. Similar to Bates, Kahle and Stulz (2009), the coefficients on net working capital, leverage, and investment are negative, while the coefficients on the market-to-book ratio are positive. The coefficients on cash flow are negative, while similar to Han and Qiu (2007), the coefficients on cash flow volatility are positive. Finally, more diversified firms, as measured by the number of classes in which they file patents, tend to hold less cash.

Overall, the results in Table 2 provide very strong support for the model's prediction of a positive relation between the cost of external financing and equilibrium cash holdings.

### *3.2.2. Tests of Prediction 2*

According to Prediction 2, cash holdings are expected to be increasing in innovation efficiency for firms that face relatively low costs of external financing, while cash holdings are expected to be decreasing in innovation efficiency for firms with relatively expensive access to external capital. To test this prediction, we split the sample to subsamples of firms with relatively low estimated external financing

costs and subsamples of firms with relatively high financing costs and estimate Eq. (30) within these two subsamples. Firm-years with low (high) financing costs are defined as a) those belonging to the top (bottom) three deciles of size in a given year, b) those belonging to the top (bottom) three deciles of age in a given year, c) firms that pay dividends or repurchase shares in a given year (firms that do not distribute cash to shareholders), and d) firms that are followed by more than one analyst in a given year (firms that do not have analyst coverage in a given year).

To save space, Table 3 reports only the coefficients on the proxy for innovation efficiency,  $\tilde{\delta}_{i,t}$ , obtained by estimating Eq. (30) in the high- $\alpha$  and low- $\alpha$  subsamples. Bold numbers in the low- $\alpha$  columns indicate that the difference between the coefficient estimates in the low- $\alpha$  and high- $\alpha$  samples is significant at the five per cent level. The coefficients on other variables are generally consistent with those reported in Table 2. Table 3 has three panels. In the first, we use the number of citations per million dollar of R&D stock as a proxy for innovation efficiency. In the second and third panels, we use citations-to-lagged R&D expenditures as a measure of  $\delta$ . In the second panel, we include cash flow volatility in the set of control variables, while in the third panel we exclude it.

Insert Table 3 here

The relation between cash holdings and innovation efficiency is significantly negative within the small-firm (high- $\alpha$ ) subsample in all three panels, while this relation is significantly positive within the large-firm (low- $\alpha$ ) subsample in all three panels, consistent with Prediction 2; the difference between the coefficients on  $\delta$  in the two samples is statistically significant. More importantly, both the negative relation in the small-firm subsample and the positive relation in the large-firm subsample are economically significant. In the former subsample, a firm in the first quartile of innovation efficiency has a cash-to-asset ratio that is 1.5 - 3 percentage points higher than that of a firm in the third quartile of innovation efficiency, *ceteris paribus*. In the latter subsample, the cash-to-assets ratio of a firm in the first quartile of innovation efficiency is 2.5 - 4 percentage points lower than that of a firm in the third quartile of innovation efficiency.

Similar evidence is obtained when we use the dividend-and-repurchase-based sample split. Among firms that pay dividends or repurchase shares (low- $\alpha$  firms), increasing innovation efficiency from the 25<sup>th</sup> to 75<sup>th</sup> percentile raises cash holdings by 3 - 4 percentage points. Among firms that do not distribute cash (high- $\alpha$  firms), moving from the first to the third quartile of innovation efficiency reduces cash holdings by 2 - 3.5 percentage points. In both subsamples the coefficients on innovation efficiency are highly statistically significant in all three panels, as are the differences between the coefficients between the two subsamples.

Similarly, relatively old (low- $\alpha$ ) firms tend to have positive and statistically and economically significant coefficients on innovation efficiency in cash holdings regressions. The relation between cash holdings and innovation efficiency for relatively young (high- $\alpha$ ) firms depends on the sample and the measure of innovation efficiency (it is positive in two panels and negative in one, and is generally statistically insignificant), but it is always less positive (more negative) than the relation within the sample of relatively old firms. Similarly, firms covered by multiple analysts (low- $\alpha$  firms) exhibit a positive and statistically and economically significant relation between innovation efficiency and cash holdings. Increasing innovation efficiency from the first-quartile level to the third-quartile level raises cash holdings by 2.5 - 4 percentage points in that subsample. In contrast, the coefficients on innovation efficiency are generally close to zero and insignificant in the no-analyst-coverage (high- $\alpha$ ) subsample.

To summarize, the results in Table 3 generally support our model's prediction regarding the relation between innovation efficiency and cash holdings. The effect of innovation efficiency on observed cash holdings depends crucially on the costs of external financing that firms face. For relatively financially unconstrained firms, this relation is positive and economically and statistically significant. For relatively financially constrained firms, the relation is significantly negative for two proxies for external financing costs and is insignificant for the other two proxies for the costs of external financing.

### 3.2.3. Tests of Prediction 3

According to the model, the effect of intensity of product market competition,  $\gamma$ , on firms' cash holdings is expected to depend on both the cost of external financing,  $\alpha$ , and innovation efficiency,  $\delta$ . In particular the model shows that the relation between  $\gamma$  and cash holdings is generally positive, except for firms with relatively low costs of external financing and relatively low innovation efficiency. Thus, for the purposes of testing Prediction 3, we split the sample into a subsample of "low- $\alpha$ , low- $\delta$ " firms and "all other" firms. We define the "low- $\alpha$ , low- $\delta$ " subsample in four different ways, according to our four proxies for  $\alpha$ : low  $\alpha$  firms belong to a) the highest three size deciles, b) the highest three age deciles, c) the highest three deciles of dividend-and-repurchase-to-assets ratio,<sup>14</sup> and d) coverage by multiple analysts. Similar to Table 3, in the first panel we use the citations-to-R&D-stock-based measure of innovation efficiency, while in the second and third panels we use the citations-to-lagged-R&D-based measure of  $\delta$ . Low- $\delta$  firms are those belonging to the lowest three deciles of one of the two innovation efficiency measures.

Insert Table 4 here

The results in the "other" subsamples are consistent with the model's prediction. For all four measures of external financing cost and for both measures of innovation efficiency, the coefficients on the proportion of citations to patents that firms were granted in their main patent class, which is our proxy for product substitutability and intensity of product market competition, are positive and highly statistically significant. They are also economically sizeable. Moving from the 25<sup>th</sup> to 75<sup>th</sup> percentile of the intensity of competition measure (from 0.46 to 1) results in an increase of 1.9 - 3.7 percentage points in the cash-to-assets ratio, *ceteris paribus*.

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<sup>14</sup>Note that our definition of "low- $\alpha$ " firms in this case is different from the one we use in Table 3, where any firm paying dividends or repurchasing shares was defined as "low- $\alpha$ ". The reason is that the cutoff value of  $\alpha$  below which the relation between cash holdings and intensity of competition is negative is typically substantially lower than the cutoff value of  $\alpha$  below which the relation between cash holdings and innovation efficiency is positive.

The results in the low- $\alpha$ , low- $\delta$  subsample are generally very different. While for most proxies for  $\alpha$  the coefficients on the intensity of competition proxy are positive and significant (the exception is firm size, where the coefficients on intensity of competition are insignificant statistically and economically), these coefficients are substantially lower than the coefficients in the “other” subsample when  $\alpha$  is defined according to firm age and dividend payments. The only result that is clearly inconsistent with the model is that for the low- $\alpha$ , low- $\delta$  subsample defined based on coverage by multiple analysts. The coefficients on the intensity of competition in that sample are higher than those in the “other” sample, inconsistent with the model, although the differences are not statistically significant.

Overall, Table 4 presents mixed evidence. On the one hand, the fact that the relation between our proxy for competition intensity and cash holdings is universally positive and statistically and economically significant provides support for the model. On the other hand, the positive and sometimes significant coefficients on competition intensity in the subsamples of firms with relatively low costs of external financing and low innovation efficiency are inconsistent with Prediction 3.

#### 3.2.4. *Tests of Prediction 4*

Prediction 4 states that the relation between firms’ equilibrium cash holdings and the number of innovating rivals in their industries is expected to be hump-shaped: firms’ equilibrium cash holdings are expected to be increasing in the number of rivals when the latter is low and cash holdings are predicted to start decreasing in the number of rivals when it is sufficiently high. We examine this prediction by augmenting the regression in Eq. (30) by the number of product market rivals in an industry,  $\tilde{N}_{k,t}$ , and its square,  $\tilde{N}_{k,t}^2$ :

$$Cash_{(i,t) \in k} = \beta_0 + \beta_1 \tilde{\alpha}_{i,t} + \beta_2 \tilde{\delta}_{i,t} + \beta_3 \tilde{\gamma}_{k,t} + \beta_4 \tilde{N}_{k,t} + \beta_5 \tilde{N}_{k,t}^2 + \overrightarrow{\beta_6 X_{i,t}} + \varepsilon_{i,t}. \quad (36)$$

A hump-shaped relation between industry mean cash holdings and the number of firms in the industry would be consistent with positive  $\beta_4$  and negative  $\beta_5$ .

The results of estimating Eq. (36) are presented in Table 5. Similar to Table 1, the three columns

correspond to three different subsamples. In the first column we use the sample of firm-years for which we can estimate capital stock, while in the second and third column the sample consists of firm-years with non-missing lagged R&D expenditures.

Insert Table 5 here

Consistent with Prediction 4, the relation between the number of firms competing for innovation in a given patent class and the mean cash holdings of these firms is positive for a relatively low number of firms, as evidenced by the significantly positive coefficient on  $\tilde{N}_{k,t}$ . This finding is consistent with the results in Morellec and Nikolov (2009), who report a positive relation between a firm's cash holdings and the number of firms in the firm's SIC or NAICS industry. However, this relation seems to reverse as the number of firms increases, as follows from the negative coefficients on  $\tilde{N}_{k,t}^2$ , which are statistically significant in two out of three specifications. The inflection point, given by  $-\frac{\beta_4}{2\beta_5}$ , is below one, suggesting that the relation between cash-to-assets and  $\tilde{N}_{k,t}$  turns negative at a low number of rivals.

Overall, most of the empirical results that we report in this section are consistent with the model's comparative statics and, more generally, with the strategic motive for holding cash in a situation in which multiple firms compete in innovation development and implementation.

## 4. Conclusions

We develop a model of strategic cash holdings by innovating firms. Firms compete by funding R&D expenditures that may result in technological innovations. Firms that succeed in developing their innovations obtain an option to implement them by investing in production facilities. An investment in a production facility can be financed by internal and/or costly external funds.

Our model illustrates the strategic reason for hoarding cash by innovating firms. By having access to a larger pool of internal funds at the time of potential investment in a production facility, a

firm commits to implementing potential technological innovation in more states of the world, given the wedge between the costs of external and internal funds. This commitment lowers the payoff to the firm's competitors from both investing in R&D and from implementing successful innovations, indirectly benefiting the firm. Firms take into account the effects of their cash holdings on the choices of rivals' strategies when choosing their cash levels. As a result, firms choose higher cash holdings in equilibrium than the level that would maximize their combined value. This result is similar to a situation in which firms competing in an output market choose excessively high debt levels in order to commit to more aggressive output market strategies. The strategic motive for hoarding cash by innovating firms in our model is related to the deep-pockets theory, according to which the cash of an incumbent serves as a deterrent for potential entrants into an industry. In our case, a firm's cash holdings discourage investments in development and implementation of innovations by the firm's rivals.

Our model provides a possible explanation for the observed temporal increase in average cash holdings, particularly among R&D-intensive firms. In addition, the model has multiple cross-sectional empirical implications regarding the relations between a firm's cash holdings on one side and the cost of external financing, the degree of innovation efficiency, the intensity of product market competition in the firm's industry, and the industry structure on the other side.

Because of the multi-stage nature of the problem faced by innovating firms, some of the comparative statics of our model and the resulting empirical predictions are more subtle than those that could be obtained in a standard deep-pockets model. One of the main reasons is that in our setting, when a firm decides how much to invest in R&D and how much cash to hoard, it faces uncertainty regarding the structure of the potential future output market, since the firm, as well as each of its potential competitors, cannot guarantee that their innovations would succeed.

We test our model's prediction using the NBER Patent Data Project, which is instrumental in identifying firms' areas of technological innovation and in constructing measures of innovation efficiency, intensity of competition, and industry structure. We find that innovation efficiency is positively re-

lated to cash holdings within a subsample of firms with relatively low costs of external funds, while it is negatively related to cash holdings within a subsample of firms facing relatively high external financing costs. We also find that the intensity of product market competition is generally positively related to firms' observed cash holdings. Finally, the relation between cash holdings and the number of product market rivals is found to be hump-shaped.

While we believe that our model and empirical evidence highlight an important motive for holding cash by innovating firms, and we provide a possible explanation for the documented temporal increase in cash holdings during the last decades, especially within a subset of firms actively pursuing innovation, many important questions remain to be answered. On the theory side, it would be interesting to introduce firm heterogeneity and analyze its effects on equilibrium cash holdings. Also, relating optimal cash holdings to the nature of the R&D process by splitting the R&D stage of the model into multiple substages could provide additional insights into strategic cash holding choices by innovative firms. Multi-stage R&D may affect optimal cash holdings because of the complementarities across R&D investments in various sub-stages. In addition, Phillips and Zhdanov (2012) show that optimal innovation may be related to acquisition market activity. Extending our model to allow for horizontal acquisitions in various stages of the game may provide additional empirical predictions regarding firms' optimal cash holdings. On the empirical side, while our tests are suggestive of the strategic motive for holding cash, testing our model's predictions using a natural experiment in which some firms face shocks to their innovation efficiency or intensity of competition could provide further evidence regarding the determinants of innovating firms' cash holdings.<sup>15</sup>

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<sup>15</sup>An example of such a natural experiment is recent work by Retzl (2011), who examines the effects of changes in patentability on innovative firms' cash holdings.

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**Table 1.** Summary Statistics

	Mean	Std. Dev.	25%	50%	75%	Min	Max	N
Cash	0.207	0.236	0.032	0.106	0.302	0.001	0.997	27864
Market-to-Book	1.953	2.089	0.806	1.230	2.180	0.006	13.215	27622
Net Working Capital	0.132	0.184	0.006	0.130	0.262	-0.421	0.536	27147
Cash Flow	0.011	0.261	0.005	0.077	0.126	-1.341	0.458	27858
Investment	0.057	0.050	0.023	0.045	0.077	-0.019	0.264	27863
Leverage	0.199	0.179	0.038	0.175	0.302	0.000	0.849	27800
Cash Flow Volatility	0.030	0.044	0.008	0.014	0.032	0.000	0.280	20143
Size	2797.481	17202.413	37.514	162.928	953.423	0.002	798812.375	27863
Dividends and Repurchases	0.037	0.706	0.000	0.007	0.031	0.000	79.035	27864
Dividends and Repurchases (Dummy)	0.609	0.488	0.000	1.000	1.000	0.000	1.000	27864
Age	37.335	38.332	10.000	20.000	57.000	1.000	232.000	27864
Analysts	3.081	4.609	0.000	1.000	4.000	0.000	32.000	27864
Proportion of Citations (Main Class)	0.714	0.297	0.463	0.785	1.000	0.039	1.000	25752
Patent Classes	7.298	16.203	1.000	2.000	5.000	1.000	182.000	27864
Patents	27.685	124.796	1.000	3.000	10.000	1.000	3652.000	27864
Citations	238.358	1128.545	6.000	23.000	88.000	0.000	40868.000	27864
Citations/R&D Stock	2.571	5.657	0.110	0.660	2.310	0.000	38.745	12819
Citations/R&D	15.623	41.846	0.595	3.096	11.323	0.000	316.568	22667
Firms (Number)	12.507	17.645	3.000	6.000	14.000	1.000	108.000	27864

This table reports the mean, standard deviation, 25% percentile, 50% percentile, 75% percentile, minimum value, maximum value, and number of available observations for the variables used in the empirical analysis. *Cash* is the amount of cash and cash equivalents (Compustat item CHE) at time  $t$  over the value of total assets (item AT) at time  $t - 1$ . *Market-to-Book* is the ratio of the firm's market value over the firm's book value. We follow Davis, Fama and French (2000) and define book equity as stockholder equity (item SEQ) plus balance sheet deferred taxes and investment tax credit (item TXDITC, if available) minus the book value of preferred stock. Preferred stock is defined as PSTKRV or PSTKL or PSTK in this order of availability. If SEQ is missing, stockholder equity is defined as the book value of common equity (item CEQ) plus the par value of preferred stock (item PSTKL). If SEQ and CEQ are both missing, then stockholder equity is defined as total assets (item AT) minus total liabilities (item LT). Market equity is the fiscal-year-end share price (item PRCC F) multiplied by the number of common shares outstanding (item CSHO). *Net Working Capital* is computed as the difference between working capital (item WCAP) and cash (item CHE) at time  $t$  over the value of total assets (item AT) at time  $t - 1$ . *Cash Flow* is defined as net income before extraordinary items (item IB) plus depreciation (item DP) at time  $t$  over the value of total assets (item AT) at time  $t - 1$ . *Investment* is defined as investment in physical capital (item CAPX) net of sales of property, plant and equipment (item SPPE, set to zero when missing) at time  $t$  over the value of total assets (item AT) at time  $t - 1$ . *Leverage* is the sum of long-term debt (item DLTT) and debt in current liabilities (item DLC) at time  $t$  over the value of total assets (item AT) also at time  $t$ . *Cash Flow Volatility* at time  $t$  is the standard deviation of the previous 16 quarterly cash flows. A quarterly cash flow is defined as net income before extraordinary items (item IBQ) plus depreciation (item DPQ) in quarter  $j$  over the value of total assets (item ATQ) in quarter  $j - 1$ . *Size* is the book value of assets (item AT) at time  $t - 1$  deflated using the Consumer Price Index (CPI). *Dividends and Repurchases* is the sum of cash dividends (item DV) and the purchase of common and preferred stock (item PRSTKC) at time  $t$  over the value of total assets (item AT) at time  $t - 1$ . *Dividends and Repurchases (Dummy)* is a dummy variable that takes the value of one if the variable *Dividends and Repurchases* is positive and zero otherwise. *Age* is the difference between the year of observation and the earlier of the founding year and incorporation year or the first year the firm appears in Compustat, in that order of availability. *Analysts* is the number of unique analysts providing estimates of the firm's annual earnings per share (NUMEST) at time  $t$  as reported in the Institutional Brokers' Estimate System (I/B/E/S). *Citations* is the total number of citations (item ALLCITES) at time  $t$ . *Proportion of Citations (Main Class)* is the mean proportion of patents that belong to a firm's main patent class. *Patent Classes* is the number of technology classes in which the firm filed patents (item NCLASS) at time  $t$ . *Patents* is the number of patents (item PATENT) granted at time  $t$ . *Citations/R&D Stock* is the ratio of the number of citations at time  $t$  over the R&D capital stock at time  $t - 1$ . Appendix A reports the procedure used to build the R&D capital stock at the firm level. *Citations/R&D* is the ratio of the number of citations at time  $t$  over R&D expenditures (item XRD) at time  $t - 1$ . *Rivals* is the number of firms that have filed patents in a firm's main patent class at time  $t$ . We use the NBER Patent Data Project for the variables *Citations*, *Classes*, *Patents*, and *Rivals*. The data are at an annual frequency over the period 1976–2006 and all ratios not bounded by 0 and 1 are winsorized at the top and bottom 1%.

**Table 2.** Cash Holdings and the Costs of External Financing

	Citations/R&D Stock				Citations/R&D I				Citations/R&D II			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Net Working Capital	-0.367*** (0.037)	-0.318*** (0.034)	-0.327*** (0.034)	-0.326*** (0.036)	-0.404*** (0.039)	-0.337*** (0.036)	-0.348*** (0.036)	-0.348*** (0.039)	-0.448*** (0.033)	-0.384*** (0.032)	-0.404*** (0.032)	-0.415*** (0.035)
Market-to-Book	0.023*** (0.002)	0.023*** (0.002)	0.024*** (0.002)	0.025*** (0.002)	0.021*** (0.002)	0.022*** (0.002)	0.023*** (0.002)	0.024*** (0.002)	0.018*** (0.001)	0.020*** (0.001)	0.020*** (0.001)	0.022*** (0.001)
Cash Flow	-0.083*** (0.028)	-0.112*** (0.031)	-0.106*** (0.031)	-0.116*** (0.032)	-0.081*** (0.019)	-0.122*** (0.024)	-0.117*** (0.023)	-0.129*** (0.026)	-0.107*** (0.016)	-0.149*** (0.021)	-0.147*** (0.019)	-0.165*** (0.022)
Leverage	-0.316*** (0.019)	-0.333*** (0.018)	-0.349*** (0.018)	-0.340*** (0.018)	-0.340*** (0.018)	-0.367*** (0.017)	-0.387*** (0.017)	-0.381*** (0.017)	-0.405*** (0.016)	-0.434*** (0.014)	-0.454*** (0.014)	-0.452*** (0.014)
Investment	-0.488*** (0.067)	-0.530*** (0.065)	-0.528*** (0.063)	-0.514*** (0.067)	-0.509*** (0.067)	-0.553*** (0.067)	-0.551*** (0.065)	-0.526*** (0.068)	-0.508*** (0.059)	-0.558*** (0.060)	-0.550*** (0.058)	-0.523*** (0.061)
Cash Flow Volatility	0.425*** (0.092)	0.424*** (0.094)	0.470*** (0.099)	0.598*** (0.096)	0.328*** (0.073)	0.381*** (0.077)	0.424*** (0.081)	0.549*** (0.077)				
Classes (number, '000)	-0.049 (0.162)	-0.620*** (0.149)	-0.680*** (0.163)	-0.771*** (0.174)	0.141 (0.143)	-0.691*** (0.151)	-0.773*** (0.161)	-0.889*** (0.180)	0.205 (0.127)	-0.794*** (0.156)	-0.741*** (0.164)	-0.919*** (0.183)
Citations/R&D Stock (Log)	-0.001 (0.002)	0.005*** (0.002)	0.007*** (0.002)	0.008*** (0.002)								
Citations/R&D (Log)					-0.011*** (0.002)	-0.001 (0.001)	0.000 (0.002)	0.002 (0.001)	-0.011*** (0.002)	0.003* (0.001)	0.003 (0.002)	0.005*** (0.002)
Proportion of Citations (Main Class) Size	-0.009 (0.003)	0.020* (0.003)	0.033*** (0.003)	0.040*** (0.003)	-0.029*** (0.003)	0.016 (0.003)	0.031*** (0.003)	0.038*** (0.003)	-0.019** (0.003)	0.035*** (0.003)	0.047*** (0.003)	0.061*** (0.003)
Age (Log)		-0.041*** (0.004)				-0.041*** (0.004)				-0.037*** (0.003)		
Dividend Dummy			-0.050*** (0.009)				-0.060*** (0.010)				-0.075*** (0.009)	
Analysts (Number)				-0.001 (0.001)				-0.001** (0.001)				-0.002*** (0.001)
Constant	0.388*** (0.026)	0.404*** (0.025)	0.290*** (0.018)	0.250*** (0.015)	0.484*** (0.032)	0.422*** (0.029)	0.317*** (0.020)	0.269*** (0.016)	0.538*** (0.029)	0.436*** (0.021)	0.367*** (0.019)	0.312*** (0.016)
Observations	10,462	10,462	10,462	10,462	14,643	14,643	14,643	14,643	20,485	20,485	20,485	20,485
Adjusted R-squared	0.480	0.495	0.477	0.467	0.513	0.517	0.503	0.490	0.528	0.526	0.521	0.503

This table reports the regression results of

$$Y_{i,t} = \gamma_0 + \gamma_t + \beta_1 \mathbf{X}_{i,t} + \beta_2 \tilde{\alpha}_{i,t} + \varepsilon_{i,t}, \quad i = 1, \dots, N, \quad t = 1, \dots, T,$$

where the dependent variable is  $Cash_{i,t}$ ,  $\gamma_0$  is a constant,  $\gamma_t$  is a year dummy,  $\beta_1$  is a  $(1 \times k)$  vector of coefficients,  $\mathbf{X}_{i,t}$  is a  $(k \times 1)$  vector of control variables,  $\beta_2$  is a coefficient,  $\tilde{\alpha}_{i,t}$  is a variable that proxies for firm's  $i$  cost of external financing at time  $t$ , and  $\varepsilon_{i,t}$  is an i.i.d. normally distributed error term. The vector of control variables includes *Net Working Capital*, *Market-to-Book*, *Cash Flow*, *Leverage*, *Investment*, *Cash Flow Volatility*, *Classes*, *Citations/R&D Stock*, *Citations/R&D I*, and *Proportion of Citations (Main Class)*. Table 1 reports the definitions of all control variables included in  $\mathbf{X}_{i,t}$ . For each subsample, we use four different proxies for external financing cost. *Size* is the natural logarithm of book assets (item AT) at time  $t - 1$  deflated using the Consumer Price Index (CPI). *Dividend Dummy* takes a value of zero if the variable *Dividends and Repurchases* is non-positive and a value of one otherwise. *Age* is the difference between the year of observation and the earlier of the founding year and incorporation year or the first year the firm appears in Compustat, in that order of availability. *Analysts* is the number of unique analysts providing estimates of the firm's annual earnings per share (NUMEST) at time  $t$  as reported in the Institutional Brokers' Estimate System (I/B/E/S). In the first subsample (*Citations/R&D Stock*), we use the variable *Citations/R&D Stock* to proxy for R&D efficiency. In the second subsample (*Citations/R&D I*), we use the variable *Citations/R&D I* to proxy for R&D efficiency. In the third subsample (*Citations/R&D II*), we use the variable *Citations/R&D II* to proxy for R&D efficiency and we exclude *Cash Flow Volatility* from the set of the control variables. *Observations* is the number of firm-year observations and *R-squared* is the adjusted R-squared. The data are at an annual frequency over the period 1976–2006 and all ratios not bounded by 0 and 1 are winsorized at the top and bottom 1%. The 1%, 5%, and 10% significance levels are denoted with \*\*\*, \*\*, and \*, respectively. Standard errors are clustered at the industry level and reported in parentheses.

**Table 3.** Cash Holdings and R&D Efficiency

Proxy for $\alpha$	Size		Age		Dividends		Analysts	
	high $\alpha$	low $\alpha$	high $\alpha$	low $\alpha$	high $\alpha$	low $\alpha$	high $\alpha$	low $\alpha$
<b>Citations/R&amp;D Stock</b>								
Citations/R&D Stock	-0.010** (0.005)	<b>0.011***</b> (0.003)	0.005 (0.004)	0.006*** (0.002)	-0.008** (0.003)	<b>0.013***</b> (0.002)	0.002 (0.003)	<b>0.016***</b> (0.003)
Observations	2,219	3,805	989	4,124	3,354	7,108	3,143	5,468
Adjusted R-squared	0.493	0.404	0.502	0.387	0.443	0.449	0.485	0.465
<b>Citations/R&amp;D I</b>								
Citations/R&D	-0.015*** (0.004)	<b>0.005*</b> (0.003)	-0.004 (0.003)	<b>0.005***</b> (0.002)	-0.014*** (0.004)	<b>0.009***</b> (0.002)	-0.001 (0.002)	<b>0.009***</b> (0.002)
Observations	3,419	5,008	2,386	5,269	5,088	9,555	4,676	7,400
Adjusted R-squared	0.520	0.392	0.525	0.382	0.459	0.463	0.497	0.483
<b>Citations/R&amp;D II</b>								
Citations/R&D	-0.014*** (0.004)	<b>0.005*</b> (0.002)	0.003 (0.002)	0.006*** (0.002)	-0.008** (0.003)	<b>0.011***</b> (0.001)	0.001 (0.002)	<b>0.015***</b> (0.002)
Observations	6,401	5,879	5,941	5,666	8,410	12,075	7,247	9,314
Adjusted R-squared	0.527	0.324	0.501	0.354	0.465	0.456	0.493	0.510

This table reports the regression coefficients on our proxy for R&D efficiency for low financially constrained firms (low  $\alpha$  sample) and high financially constrained firms (high  $\alpha$  sample). The regression equation is

$$Y_{i,t} = \gamma_0 + \gamma_t + \beta_1 \mathbf{X}_{i,t} + \beta_2 \bar{\alpha}_{i,t} + \varepsilon_{i,t}, \quad i = 1, \dots, N, \quad t = 1, \dots, T,$$

where the dependent variable is  $Cash_{i,t}$ ,  $\gamma_0$  is a constant,  $\gamma_t$  is a year dummy,  $\beta_1$  is a  $(1 \times k)$  vector of coefficients,  $\mathbf{X}_{i,t}$  is a  $(k \times 1)$  vector of variables that includes our proxy for R&D efficiency, and  $\varepsilon_{i,t}$  is an i.i.d. normally distributed error term. The vector  $\mathbf{X}_{i,t}$  includes *Net Working Capital*, *Market-to-Book*, *Cash Flow*, *Leverage*, *Investment*, *Cash Flow Volatility*, *Classes*, *Citations/R&D Stock*, *Citations/R&D*, and *Proportion of Citations (Main Class)*. Table 1 reports the definitions of all variables included in  $\mathbf{X}_{i,t}$ . We use four different proxies for the cost of external financing. When the proxy is *Size*, firms are classified as low  $\alpha$  if they belong to the top 30% of the *Size* distribution and high  $\alpha$  if they belong to the bottom 30% of the *Size* distribution at time  $t$ . When the proxy is *Age*, firms are classified as low  $\alpha$  if they belong to the top 30% of the *Age* distribution and high  $\alpha$  if they belong to the bottom 30% of the *Age* distribution at time  $t$ . When the proxy is *Dividends and Repurchases*, firms are classified as low  $\alpha$  if they report a positive payout and high  $\alpha$  if they report a zero payout at time  $t$ . When the proxy is *Analysts* (the number of analyst estimates), firms are classified as low  $\alpha$  if they report a number of analyst estimates larger than one (one being the median number of analyst estimates) and high  $\alpha$  if they report a zero or missing number of analyst estimates at time  $t$ . In the first subsample (*Citations/R&D Stock*), we use the variable *Citations/R&D Stock* to proxy for R&D efficiency. In the second subsample (*Citations/R&D I*), we use the variable *Citations/R&D* to proxy for R&D efficiency. In the third subsample (*Citations/R&D II*), we use the variable *Citations/R&D Stock* to proxy for R&D efficiency and we exclude *Cash Flow Volatility* from the set of control variables. *Observations* is the number of firm-year observations and *R-squared* is the adjusted R-squared. The data are at an annual frequency over the period 1976–2006 and all ratios not bounded by 0 and 1 are winsorized at the top and bottom 1%. The 1%, 5%, and 10% significance levels are denoted with \*\*\*, \*\*, and \*, respectively. Standard errors are clustered at the industry level and reported in parentheses. Bold coefficients in the low  $\alpha$  columns are significantly different from coefficients in the high  $\alpha$  columns at a 5% level.

Table 4. Cash Holdings and Product Market Competition

Proxy for $\alpha$	Size		Age		Dividends		Analysts	
	low $\alpha$ low $\delta$	Other	low $\alpha$ low $\delta$	Other	low $\alpha$ low $\delta$	Other	low $\alpha$ low $\delta$	Other
<b>Citations/R&amp;D Stock</b>								
Proportion of Citations (Main Class)	0.001 (0.017)	0.035*** (0.013)	0.025** (0.012)	0.044*** (0.014)	0.029 (0.018)	0.044*** (0.014)	0.057** (0.027)	0.042*** (0.013)
Observations	1,464	8,998	1,447	9,015	840	9,622	1,015	10,181
Adjusted R-squared	0.374	0.477	0.353	0.471	0.441	0.472	0.419	0.467
<b>Citations/R&amp;D I</b>								
Proportion of Citations (Main Class)	-0.001 (0.013)	<b>0.037***</b> (0.011)	0.020* (0.011)	0.044*** (0.013)	0.018 (0.016)	0.043*** (0.012)	0.058** (0.024)	0.040*** (0.012)
Observations	2,015	12,628	1,821	12,822	1,123	13,520	1,514	13,129
Adjusted R-squared	0.364	0.503	0.370	0.495	0.409	0.497	0.443	0.497
<b>Citations/R&amp;D II</b>								
Proportion of Citations (Main Class)	0.002 (0.014)	<b>0.061***</b> (0.010)	0.030*** (0.010)	<b>0.068***</b> (0.010)	0.050*** (0.018)	0.068*** (0.010)	0.082*** (0.025)	0.066*** (0.010)
Observations	2,461	18,024	1,965	18,520	1,313	19,172	1,669	18,816
Adjusted R-squared	0.311	0.515	0.364	0.505	0.374	0.508	0.427	0.509

This table reports the regression coefficients on our proxy for the intensity of product market competition (*Proportion of Citations (Main Class)*) for low financially constrained and low innovation efficiency firms (*low  $\alpha$  low  $\delta$*  sample) and all the other firms (*other* sample). The regression equation is

$$Y_{i,t} = \gamma_0 + \gamma_t + \beta_1 \mathbf{X}_{i,t} + \varepsilon_{i,t}, \quad i = 1, \dots, N, \quad t = 1, \dots, T,$$

where the dependent variable is  $Cash_{i,t}$ ,  $\gamma_0$  is a constant,  $\gamma_t$  is a year dummy,  $\beta_1$  is a  $(1 \times k)$  vector of coefficients,  $\mathbf{X}_{i,t}$  is a  $(k \times 1)$  vector of variables that includes our proxy for product market competition, and  $\varepsilon_{i,t}$  is an i.i.d. normally distributed error term. The vector  $\mathbf{X}_{i,t}$  includes *Net Working Capital*, *Market-to-Book*, *Cash Flow*, *Leverage*, *Investment*, *Cash Flow Volatility*, *Classes*, *Citations/R&D Stock*, *Citations/R&D*, and *Proportion of Citations (Main Class)*. Table 1 reports the definitions of all variables included in  $\mathbf{X}_{i,t}$ . We use four different proxies for the cost of external financing. When the proxy is *Size*, firms are classified as *low  $\alpha$  low  $\delta$*  if they belong to the top 30% of the *Size* distribution and to the bottom 30% of the innovation efficiency distribution at time  $t$ . When the proxy is *Age*, firms are classified as *low  $\alpha$  low  $\delta$*  if they belong to the top 30% of the *Age* distribution and to the bottom 30% of the innovation efficiency distribution at time  $t$ . When the proxy is *Dividends and Repurchases*, firms are classified as *low  $\alpha$  low  $\delta$*  if they belong to the top 30% of the *Dividends and Repurchases* distribution (only positive values are considered in this case) and to the bottom 30% of the innovation efficiency distribution at time  $t$ . When the proxy is *Analysts* (the number of analyst estimates), firms are classified as *low  $\alpha$  low  $\delta$*  if they belong to the top 30% of *Analysts* distribution (only positive values are considered in this case) and to the bottom 30% of the innovation efficiency distribution at time  $t$ . In the first subsample (*Citations/R&D Stock*), we use the variable *Citations/R&D Stock* to proxy for R&D efficiency. In the second subsample (*Citations/R&D I*), we use the variable *Citations/R&D* to proxy for R&D efficiency. In the third subsample (*Citations/R&D II*), we use the variable *Citations/R&D Stock* to proxy for R&D efficiency and we exclude *Cash Flow Volatility* from the set of control variables. *Observations* is the number of firm-year observations and *R-squared* is the adjusted R-squared. The data are at an annual frequency over the period 1976–2006 and all ratios not bounded by 0 and 1 are winsorized at the top and bottom 1%. The 1%, 5%, and 10% significance levels are denoted with \*\*\*, \*\*, and \*, respectively. Standard errors are clustered at the industry level and reported in parentheses. Bold coefficients in the *Other* columns are significantly different from coefficients in the *low  $\alpha$  low  $\delta$*  columns at a 5% level.

**Table 5.** Cash Holdings and Number of Rivals

	Citations/R&D Stock	Citations/R&D I	Citations/R&D II
Net Working Capital	-0.311*** (0.031)	-0.332*** (0.033)	-0.396*** (0.029)
Market-to-Book	0.022*** (0.002)	0.022*** (0.002)	0.020*** (0.002)
Cash Flow	-0.109*** (0.030)	-0.121*** (0.022)	-0.157*** (0.018)
Leverage	-0.340*** (0.019)	-0.378*** (0.017)	-0.446*** (0.014)
Investment	-0.490*** (0.064)	-0.497*** (0.060)	-0.499*** (0.051)
Cash Flow Volatility	0.564*** (0.097)	0.516*** (0.075)	
Classes (number, '000)	-0.766*** (0.181)	-0.911*** (0.187)	-0.943*** (0.183)
Citations/R&D Stock	0.011*** (0.002)		
Citations/R&D		0.005*** (0.002)	0.008*** (0.001)
Proportion of Citations (Main Class)	0.041*** (0.012)	0.039*** (0.011)	0.065*** (0.009)
<b>N Firms ('000)</b>	<b>1.733***</b> <b>(0.663)</b>	<b>2.202***</b> <b>(0.752)</b>	<b>2.540***</b> <b>(0.822)</b>
<b>N Firms ('000, squared)</b>	<b>-5.105</b> <b>(6.555)</b>	<b>-8.918</b> <b>(7.424)</b>	<b>-13.252</b> <b>(8.139)</b>
Constant	0.230*** (0.013)	0.239*** (0.013)	0.273*** (0.012)
Observations	10,462	14,643	20,485
Adjusted R-squared	0.478	0.503	0.514

This table reports the regression coefficients of the following linear equation:

$$Y_{i,t} = \gamma_0 + \gamma_t + \beta_1 \mathbf{X}_{i,t} + \beta_2 \tilde{N}_{k,t} + \beta_3 \tilde{N}_{k,t}^2 + \varepsilon_{i,t}, \quad i = 1, \dots, N, \quad t = 1, \dots, T,$$

where the dependent variable is  $Cash_{i,t}$ ,  $\gamma_0$  is a constant,  $\gamma_t$  is a year dummy,  $\beta_1$  is a  $(1 \times k)$  vector of coefficients,  $\mathbf{X}_{i,t}$  is a  $(k \times 1)$  vector of control variables,  $\beta_2$  and  $\beta_3$  are coefficients,  $\tilde{N}_{k,t}$  is the number of firm  $i$ 's rivals at time  $t$ ,  $\tilde{N}_{k,t}^2$  is the square of the number of firm  $i$ 's rivals at time  $t$ , and  $\varepsilon_{i,t}$  is an i.i.d. normally distributed error term. The vector  $\mathbf{X}_{i,t}$  includes *Net Working Capital*, *Market-to-Book*, *Cash Flow*, *Leverage*, *Investment*, *Cash Flow Volatility*, *Classes*, *Citations/R&D Stock*, *Citations/R&D*, and *Proportion of Citations (Main Class)*. Table 1 reports the definitions of all of the variables included in  $\mathbf{X}_{i,t}$ . In the first subsample (*Citations/R&D Stock*), we use the variable *Citations/R&D Stock* to proxy for R&D efficiency. In the second subsample (*Citations/R&D I*), we use the variable *Citations/R&D* to proxy for R&D efficiency. In the third subsample (*Citations/R&D II*), we use the variable *Citations/R&D Stock* to proxy for R&D efficiency and we exclude *Cash Flow Volatility* from the set of control variables. *Observations* is the number of firm-year observations and *R-squared* is the adjusted R-squared. The data are at an annual frequency over the period 1976–2006 and all ratios not bounded by 0 and 1 are winsorized at the top and bottom 1%. The 1%, 5%, and 10% significance levels are denoted with \*\*\*, \*\*, and \*, respectively. Standard errors are clustered at the industry level and reported in parentheses.