The R&D Investment-Uncertainty Relationship: Do Strategic Rivalry and Firm Size Matter?[1]

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Abstract

This paper uses a real options perspective to augment the standard R&D investment model and implements a firm-level empirical analysis to assess the practical significance of market uncertainty and its interactions with strategic rivalry and firm size. We use a measure of firm-relevant market uncertainty along with panel data and find that firms invest less in current R&D as uncertainty about market returns increases. The effect of firm-specific uncertainty on R&D investment is smaller in concentrated markets – those where strategic rivalry is more intense. Furthermore, holding access to financing constant, the effect of uncertainty on R&D investment is attenuated for large firms.

Keywords: Real Options Theory, Uncertainty, R&D, Strategic Rivalry, Firm Size

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1 Introduction

Economists view research and development (R&D) expenditure as an investment decision that is commonly understood by applying models of physical capital investment. The recent development of real options models offers a new perspective for understanding the determinants of R&D expenditure. These models highlight the influence of uncertainty when investments are at least partially irreversible and decision makers are able to choose the timing of their investments (Dixit and Pindyck 1994; Abel and Eberly 1996; Abel et al. 1996).

Real options models are a natural starting point for understanding how uncertainty influences R&D investment decisions. R&D investments satisfy the irreversibility criterion of the real options paradigm because the bulk of R&D expenditures support the salaries of research personnel and cannot be recouped if projects fail (Grabowski 1968; Dixit and Pindyck 1994). However, unlike the canonical real options model of a monopolist evaluating a single investment project, most private R&D investment is undertaken strategically by large multi-project firms. The influence of market uncertainty on investment may be different in these circumstances. For instance, the decision makers of large multi-project firms may respond less to uncertainty due to greater flexibility in R&D capacity utilization (Pindyck 1988). Strategic rivalry may introduce the threat of pre-emption and restrict the decision makers' choices about when to invest (Kulatilaka and Perotti 1998; Weeds 2002).

This paper uses a real options perspective to augment a conventional R&D investment framework and implements a firm-level empirical analysis to assess the practical significance of market uncertainty and its interactions with strategic rivalry and firm size. A number of theoretical and empirical studies examine these interrelationships in the case of physical capital investment (see, for instance, Bloom et al. 2007; Bulan 2005; Ghosal and Loungani 1996, 2000;

Grenadier 2002; Novy-Marx 2007; Weeds 2002). For R&D investment, only a handful of empirical studies explore the effects of uncertainty and none have examined how strategic rivalry and firm size affect the relationship between uncertainty and R&D investment.

In line with prior studies, we find that current R&D investment falls as market uncertainty increases. We also find that the effect of firm-specific uncertainty on R&D investment is smaller in concentrated markets. As Scott (2009) describes, these markets are "Schumpeterian" industries where R&D strategic rivalry is more intense. This result is consistent with real options models involving oligopolistic competition where pre-emption erodes the option value of waiting (Grenadier 2002; Weeds 2002). Furthermore, R&D investment by large firms is less responsive to uncertainty even after controlling for potential financial constraints. Large firms have inter-related and ongoing R&D projects and this allows R&D assets to be transferred to alternative uses within the firm. This flexibility suggests that size confers valuable marginal "operating options" that offset the effect of uncertainty without relying on the belief that large firms have greater access to financing. However, our current database is not detailed enough to pinpoint the exact source of greater flexibility and our firm size result is consistent with other non-financial possibilities. For instance, large multi-project firms may enjoy economics of scope or have other flexibilities through "portfolio effects" as described by Moel and Tufano (2002).

2 Prior Literature

In this paper, we apply a conceptual framework that generalizes a standard, but rather simple, model of firm-level R&D investment behavior. The conventional model, which is described by Grabowski and Baxter (1973) and Howe and McFetridge (1976), postulates that in each planning period the firm chooses the level of R&D investment that equates the marginal return to R&D (*mrr*) with the marginal cost of R&D capital (*mcc*). This model is related to Tobin's "marginal q" in which it is optimal for a firm to invest when the marginal valuation of an addition unit of R&D capital in the current period exceeds its marginal cost.[2] The condition determining the optimal level of R&D investment is:

(1) $mrr_t = mcc_t$

In the decades since this simple model was postulated there have been a number of significant advances in the theoretical literature on investment.[3] Although a survey of these developments is beyond the scope of this paper, an important contribution by Abel et al. (1996) shows the equivalence between the q-theory of investment and more recent models using a real options framework. Their analysis shows how investment decisions are related to future opportunities and costs. A version of their investment optimality condition can be written as:

(2) $mrr_t = mcc_t - \gamma R_t + \gamma E_t$

In this dynamic setting, mrr_t now represents the expected present value of current and future marginal revenue products of capital evaluated at the current level of capital. The mcc_t term is the current marginal cost of purchasing a unit of R&D capital. Gamma is the firm's discount factor. The second term on the right-hand side, *R*, adjusts for "reversibility" options which take into account changes in the opportunities and costs associated with disinvestment at some point in the future. Because purchasing a unit of capital today creates the opportunity to

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[2] This formulation leads to a reduced form model in which the level of R&D investment is regressed on a variety of explanatory variables related to R&D returns (*mrr*) and the cost of capital (*mcc*). See David et al. (2000) for a review of this model.

[3] For instance, refer to Dixit and Pindyck (1994), Abel and Eberly (1996, 1999). Butzen and Fuss (2002) and Carruth et al. (2000) survey the literature on investment under uncertainty.

sell this unit in the future, the marginal value of this option reduces the effective cost of capital today. The final component, *E*, adjusts for "expandability" options which take into account changes in the opportunities and costs associated with investment at some point in the future. Because purchasing a unit of capital today extinguishes the option to purchase this unit in the future, the marginal value of this option increases the effective cost of capital today. The value of an expandability option is commonly referred to as the option value of waiting.

In the literature, R&D investment is typically considered to be a completely irreversible type of capital investment since a large proportion of R&D supports the salaries of research personnel that cannot be recouped if projects fail (see, for instance, Grabowski 1968; Dixit and Pindyck 1994, p. 424). Under this assumption, the value of the reversibility option in equation (2) is zero and only the expandability option influences optimal R&D investment. So, in addition to the factors that influence *mrr* and *mcc*, factors that change the option value of waiting will also affect the incentive for current R&D investment.

Holding other factors constant, comparative static results suggest increases in uncertainty reduce the incentive for current R&D investment by increasing the marginal value of expandability options – increasing the option value of waiting. Higher uncertainty leads to a higher trigger threshold for investment. Theoretically, however, the current level of investment remains ambiguous because higher uncertainty may also increase the probability of reaching a given threshold (see, for instance, Dixit and Pindyck 1994, page 369; Abel and Eberly 1996;

Sarkar 2000; Lund 2005; Bloom et al. 2007).[4] In light of the theoretical ambiguity, the direction of the effect of uncertainty on current R&D investment must be investigated empirically.

Our review of the empirical literature identified only four published articles that examine the effect of uncertainty on R&D investment.[5] Using cash flow volatility as a proxy for firm-specific uncertainty, Minton and Schrand (1999) found higher levels of volatility are associated with lower R&D investment for a sample of public firms in the US. Analyzing a sample of OECD countries, Goel and Ram (2001) found that greater uncertainty, measured as the standard deviation in a country's inflation rate, reduces the share of R&D in GDP, but has no significant effect on the share of non-R&D investment in GDP. In two recent papers, Czarnitzki and Toole (2007, 2011) examined cross-sectional and panel data on innovative firms in the German manufacturing sector to explore how innovation policies interact with product market uncertainty. Using past revenue volatility as a proxy for uncertainty, they found that current R&D investment falls as firm-specific uncertainty increases. R&D subsidies and patents were found to partially offset the effect of uncertainty on the firm's R&D decision and thereby increase current R&D investment.

None these papers, however, examine the possibility that competition through strategic rivalry could influence how uncertainty affects current R&D investment.[6] Some theoretical

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[4] The presence of growth options or investment lags in R&D would also offset the negative effect of expandability options (Kulatilaka and Perotti 1998, Ban-Ilan and Strange 1996). Also see Abel and Eberly (1999).

[5] Bloom (2007) considers how adjustment costs may differ between R&D and fixed capital investment and presents some simulation results. There is also a growing empirical literature on the relationship between fixed capital investment and uncertainty at the project and firm levels. Recent contributions include Bulan et al. (2009), Baum et al. (2008), Bloom et al. (2007), Bulan (2005).

[6] Theoretical models incorporating strategic considerations are reviewed by Gilbert (2006) for the industrial organization literature and by Smit and Trigeorgis (2004) for the financial economics literature.

models show that strategic rivalry erodes the option value of waiting (Grenadier 2002). Using a real options model with R&D competition, Weeds (2002) finds that the incentive for current investment depends on the relative magnitudes of the option value of waiting and the expected value of pre-emption. In her model the disincentive for current R&D investment due to higher uncertainty is offset as strategic rivalry increases. In contrast, Novy-Marx (2007) presents a model in which firm heterogeneity in scope and size leads to different opportunity costs of investment. Heterogeneity prevents firms from competing directly over investment opportunities and the option value of waiting remains even if competition drives oligopoly rents to zero. In this case, heterogeneity reduces (or eliminates) the expected value of pre-emption and the disincentive for current R&D investment due to higher uncertainty is not offset by strategic rivalry. In this paper, we empirically investigate whether strategic rivalry offsets the value of expandability options.

The influence of firm size on the investment-uncertainty relationship is also an unsettled issue. Empirical studies of fixed capital investment suggest this distinction may be important. Ghosal and Loungani (2000) postulate that greater uncertainty exacerbates existing capital market imperfections due to asymmetric information (also see Himmelberg and Petersen 1994). Higher uncertainty leads to higher costs of external funds and forces small firms to reduce current investment more than large firms. Using industry-level data, they find that uncertainty reduces investment in industries dominated by small firms and has no significant effect in industries dominated by large firms. Bulan (2005) connects firm size directly to factors that affect option values by suggesting large firms possess more market power or have greater irreversibility of capital. Contrary to Ghosal and Loungani, she expects large firms to reduce current investment more than small firms as uncertainty increases. In her analysis of fixed capital investment, large firms appear to respond more to uncertainty, but the difference between large and small firms is not statistically significant.

A more appealing possibility is that large firms possess more valuable marginal "operating options" than small firms. The existence and value of an operating option derives from the flexibility a firm obtains when purchasing an additional unit of capital. Pindyck (1988) presents a model of irreversible investment and capacity choice that allows for flexibility in capacity utilization. Each unit of installed capacity gives the firm an infinite number of options to produce or not, one for each future time period. When applied to R&D investment, flexibility in the utilization is likely to be greater for large firms. With many inter-related and ongoing R&D projects, large firms have the option to shift R&D personnel and equipment across projects within the firm in response to changes in market conditions. Pindyck (1988) shows that greater uncertainty increases the value of a firm's marginal operating option and increases the incentive for current investment.[7] This offsets the negative effect on current investment acting through expandability options. Intuitively, R&D investment by larger firms should respond less to a given change in uncertainty because they hold more valuable operating options. We examine how firm size interacts with uncertainty in the empirical analysis.

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[7] In equation (2), the mrr_t term captures this effect when it is convex. (See Abel et al. (1996), footnote 13, page 763. Dixit and Pindyck (1994) also discuss the offsetting effects of operational flexibility, page 195-199, chapter 6).

3 Data and Empirical Model

3.1 Data

Our data come from the Mannheim Innovation Panel (MIP) which is an annual survey conducted by the Centre for European Economic Research (ZEW), Mannheim, Germany, since 1992. The MIP is the German part of the European-wide Community Innovation Surveys (CIS) designed to collect harmonized data on innovation in the European Community following the guidelines of the OSLO manual, the international guidelines for collecting innovation data from the business sector (Eurostat and OECD, 2005).[8] The surveys yield a representative sample of the German manufacturing sector each year covering firms with five or more employees.

From the MIP surveys, we construct a panel database consisting of 881 "innovative" firms from Germany's manufacturing sector observed between 1995 and 2001. The panel is unbalanced because firms do not respond to the survey in every year. An innovative firm is defined as a company that introduced at least one new product in the pre-sample period, that is, before the firm enters the panel database.[9] We require each firm to be observed at least three times before entering our sample. We use these pre-sample years to generate some of the explanatory variables including our proxy for the firm's perceived uncertainty in the market for innovations. Our final sample has 2,974 firm-year observations with the following structure: 21% of firms are observed twice, 23% three times, 21% four times, and the remaining 36% are

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[8] For a detailed description of the CIS, see e.g. Eurostat (2004).

[9] For the MIP survey, a new product is defined as "a product whose technological characteristics or intended uses differ significantly from those of previously produced products. Such innovations can involve radically new technologies, can be based on combining existing technologies in new uses, or can be derived from the use of new knowledge" (Olso Manual, page 31, www.oecd.org/dataoecd/35/61/2367580.pdf).

observed between 5 and 7 times. A breakout of our sample by industry is presented in Table A.1 in the appendix.

The log-level of current R&D investment for firm i at time t, $\ln R\&D_{it}$, is our dependent variable. The distribution of R&D investment is skewed above zero and this motivates our use of the logarithmic specification. Since we cannot take the log of the censored observations at $R\&D_i = 0$, we set those observations to the minimum observed positive value of R&D in the sample and interpret this observed minimum as the censoring point in the regression models. R&D is measured in millions of Deutsche Mark (1.95583 DM = 1 EURO). Consistent with what one would expect from real options behavior, one-third of the innovative firms with positive R&D in the past have at least one observation with zero R&D investment in subsequent years. Since our sample has a number of smaller private firms (the median number of employees per firm is 110), R&D investment is intermittent.[10] In regression models, we account for the censored distribution of R&D using a Tobit model.

We assume firms use their past market experience as innovators to form their expectations about future market uncertainty. Market uncertainty is measured by the coefficient of variation of past sales. We distinguish two components of past sales since our data allow us to explicitly account for sales of new products introduced in the most recent three years and sales of established products. The survey requests the respondents to classify their total sales as follows:

(a) sales with products new to the market,

(b) sales of products that are not new to the market, but new to the firm including significant

[10] This is consistent with real options behavior because the trigger values for investing and abandoning projects are higher and lower, respectively, than those predicted from standard net present value analysis. See Novy-Marx

improvements of existing products, and

(c) sales of marginally improved products and unchanged products.

We use the sum of (a) and (b) as our definition for "new product sales" and calculate the coefficient of variation, *UNC_NEW*. The coefficient of variation of older, more established product sales, *UNC_OLD*, is based on definition (c) from above. To eliminate firm size effects in sales volume, we rescaled the sales revenue figures by the number of firm employees. The number of observations available for calculating the coefficients of variation depends on the year the firm enters the panel. The number of usable observations ranges from three to nine years depending on data availability (s = 1,…,S, with S ranging between 3 and 9): [11]

$$(1) \qquad UNC_{it} = \frac{\sqrt{\frac{1}{S}\sum_{s=1}^{S}\left[\frac{R_{i,t-s}}{L_{i,t-s}} - \left(\frac{1}{S}\sum_{s=1}^{S}\frac{R_{i,t-s}}{L_{i,t-s}}\right)\right]^2}}{\frac{1}{S}\sum_{s=1}^{S}\frac{R_{i,t-s}}{L_{i,t-s}}},$$

where R_i refers to firm *i*'s sales with new products or sales with old products and L_i denotes the firm's employment.

Because our proxies for firm-level uncertainty have not been used in published research, we would like to validate this measure against external information. Based on the measurement approach used by Guiso and Parigi (1999) we searched for survey data. Somewhat fortunately, the 2005 German Community Innovation Survey asked a representative (random) sample of manufacturing firms to describe the competitive situation in their main product markets in 2004.

(2007) for a discussion of the implications from intermittent and lumpy investment behavior in a real options theoretical model. (Also see Abel and Eberly 1996; Bloom et al. 2007)

The survey asked six different questions, each allowing four possible choices: "Does not apply," "Does somewhat apply," "Does apply," and "Does strongly apply." Two of the six questions related to perceived uncertainty in the firm's main product market. The first of these referred to uncertainty about rivalry. It stated, "Reactions by competitors are difficult to anticipate." The second of these referred to uncertainty about demand. It stated, "The development of demand is difficult to forecast." Although the survey responses cannot be linked to the firms in our sample, we decided to examine the relationship between our uncertainty measure and the survey responses at the industry level. Using nineteen industry categories, we created dummy variables equal to one if the survey respondent answered "Does strongly apply" to either of the two scenarios. As a (rough) validation of our proxy, we calculated the correlation coefficient between our average measure of uncertainty, the coefficient of variation of new product sales, and the mean of the dummy variables indicating strategic and demand sources of uncertainty at the industry level.

The results are generally supportive of our proxy. The correlation coefficient between our uncertainty measure and the external survey data is 0.43 for the product market rivalry question, and 0.45 for the demand uncertainty question. While correlation values such as these are usually interpreted as indicating a moderate degree of relatedness, it should be remembered that these alternative measures were drawn from two independent datasets and represent two completely different approaches to measuring firm-level uncertainty. Scatter plots showing these relationships can be found in the appendix.

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[11] For the regression models presented below, we performed robustness checks to test the sensitivity of our results to the length of the pre-sample period used. This did not materially affect our results. If desired, these results can be obtained from the authors.

Since we are interested in how strategic rivalry and firm size affect the R&D investment-uncertainty relationship, we created interaction variables between uncertainty and our measures of industry concentration and firm size. The degree of strategic rivalry in an industry is measured using the seller concentration given by the Herfindahl index based on shares of total market sales at the 3-digit NACE level, ln(*HHI*).[12] We define industries in the upper quintile of the distribution of the Herfindahl index as highly concentrated indicating a high degree of strategic rivalry. Firm size is measured using the number of employees in the firm. We define a firm as large when it has more than 500 employees. In our sample, 14.5% of the firms are large. We checked the cut points for concentration and firm size for robustness and this is discussed in the results section below.

Papers by Caballero and Pindyck (1996) and Leahy and Whited (1996) highlight that greater industry-level and systematic (economy-wide) uncertainties are associated with lower current investment. To control for these sources of uncertainty, we calculated an industry-level measure of uncertainty and used a full set of industry and time dummy variables in the models. We calculated the coefficient of variation of total industry sales over time at the 3-digit NACE level obtained from official German industry statistics of the "Monopolies Commission" (UNC_IND_{it-1}). As we do not have information about employment at this detailed industry level, we did not normalize industry sales by the number of employees, but rather, the number of firms active in that industry in a given year.

We also constructed a proxy for firm-specific risk preferences using the firm's recent product innovation strategy. That is, firms with an aggressive product innovation strategy should

[12] NACE is the European standard industry classification. The 881 firms in our sample operate in 91 different 3-

be the *least* risk-averse firms, while those following a conservative innovation strategy should be the most risk-averse. The firm's relative innovativeness (*PASTINNO*) is calculated using its average share of new product sales relative to its industry in the pre-sample period (the same period over which we calculate our uncertainty measure).

We used the firm's patent stock, $PSTOCK_{it\text{-}1}$, to control for existing R&D capabilities. It is calculated with data from the German Patent and Trademark Office. Those data cover German patents (including EPO priority applications with German coverage) since 1978. We cumulated each firm's patents from 1978 forward using a 15% annual obsolescence rate of knowledge (see e.g. Griliches and Mairesse, 1984, or Hall, 1990, for details). This control variable enters our models in lagged form to avoid simultaneity.

Our specifications control for access to internal and external financial capital. For the availability of internal capital, we used a measure of the firm's average price-cost margin, (*PASTPCM*), in the pre-sample period:[13]

$$(2) \qquad PASTPCM_{i,t-1} = \frac{1}{S}\sum_{s=1}^{S} PCM_{i,t-s}$$

with *PCM* = (Sales – staff cost – material cost + R&D) / Sales.

As a proxy for access to external credit, we used the firm's credit rating from Creditreform, the largest German credit rating agency. We used the rating in period *t*-1 in order to avoid

digit NACE industries.

[13] See Collins and Preston (1969), or Ravenscraft (1983). Scholars who have used such measures to test for financial constraints typically add back R&D to PCM, as R&D is an expense and reduces profits in the period. If the firm would have decided not to invest in R&D, PCM would have been accordingly higher and is therefore corrected by current R&D in most empirical studies (see e.g. Harhoff, 1998). Note that many scholars used cash-flow instead of PCM (e.g. Fazzari et al., 1998), but unfortunately such information is not available to us. As the majority of firms are small and medium-sized privately owned companies, they are not obliged to publish their financial data.

endogeneity problems.[14] The rating is an index ranging from 100 to 600, where 600 is the worst and basically corresponds to bankruptcy.

Table 1 presents descriptive statistics of all variables. Note that all time-variant variables enter the right-hand side of the regressions as lagged values, so that they can be treated as predetermined.

>>> Insert Table 1 about here <<<

3.2 Empirical Model

We use two different estimators for our panel data, a pooled cross-sectional and a random effects panel estimator. The model can be written as

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\begin{aligned}
&y_{it} = \max\left(0, x_{it}\beta + c_i + u_{it}\right), \quad i = 1,2,\ldots,N, \;\; t = 1,2,\ldots,T \\
&u_{it} \mid x_i, c_i \sim N\left(0, \sigma_u^2\right)
\end{aligned}
\tag{3}
$$

where y_{it} is the dependent variable, x_{it} denotes the set of regressors, β the parameters to be estimated, and c_i the unobserved firm-specific effect, and u_{it} is the error term. First, we assume that $c_i = 0$, and thus the model can be estimated as a pooled cross-sectional model where we adjust the standard errors for firm clusters to account for the panel structure of the data. The pooled model has the advantage that it does not maintain the strict exogeneity assumption. While u_{it} has to be independent of x_{it}, the relationship between u_{it} and x_{is}, $t \neq s$, is not specified (see

[14] For some firms, there was no rating available for the preceding year. In such cases we use ratings from one or two years earlier.

Wooldridge, 2002: 538). For instance, the model allows for feedback of R&D in period t to the regressors in future periods. In the second version of the model, we apply a random-effects Tobit panel estimator allowing $c_i \neq 0$.[15] This requires the strict exogeneity assumption so the error term needs to be uncorrelated with the covariates across all time periods. In addition, the random-effects Tobit requires the assumption that c_i is uncorrelated with x_{it}. Due to these stronger assumptions, we do not necessarily consider the random effects estimator as superior to the pooled cross-sectional estimator. Note that we keep the time-invariant industry dummies in the random-effects panel model in order to reduce the error variance of the firm-specific effect.

4 Results

Table 2 presents our basic regression results. We consider three versions of the empirical specification: model A is the baseline specification and excludes the interaction variables between market uncertainty, concentration, and firm size. Model B examines how the R&D investment-uncertainty relationship is mediated by greater market concentration which we interpret as indicating greater strategic rivalry as in Scott (2009). Model C looks at how the R&D investment-uncertainty relationship differs between large and small firms. In models B and C we estimated separate slope coefficients of uncertainty for each group of interest. In model B, the groups are concentrated versus less concentrated industries. In model C, the groups are large versus small firms.

Using both pooled and random effects Tobit, model A finds that uncertainty in the market for new products significantly reduces firm-level R&D investment. This reaffirms earlier results found in Czarnitzki and Toole (2007, 2011). It is also consistent with Minton and Schrand

[15] Fixed effects Tobit estimators are inconsistent (see e.g. Cameron and Trivedi, 2005).

(1999) who found that cash flow volatility is associated with lower R&D investment. Uncertainty in the market for established products has no significant relationship with current R&D investment in any of the regression models in Table 2.

Among the control variables, industry-level uncertainty is not significant in either the pooled or random-effects regressions. Our proxy for firm risk preferences (PASTINNO) has the correct sign, but is only marginally significant in the random effects models A and B. The Herfindahl index (HHI) is not significant in either model. For the financing variables, internal funds (PASTPCM) is positive and significant in the pooled model, but insignificant in the random effects panel model. Access to external capital (RATING) is not significant in either model. Patent stock per employee and employment are positive and significant in both pooled and random effects models. Because the results for the control variables are very similar across models in Table 2, we will not discuss these variables further.

Model B looks at how strategic rivalry influences the firm-level R&D investment-uncertainty relationship. When the distribution of Herfindahl index is partitioned at the eightieth percentile, both models show that firms in upper quintile respond less to uncertainty. The Chi-squared test reported at the bottom of Table 2 shows a statistically significant difference across the two groups. If other cutoff points in the distribution of concentration are chosen, the firm-level responses to uncertainty become increasingly similar. We re-estimated the model using the 70%, 60% and 50% quantiles of HHI as cutoff points. The difference in the estimated slopes coefficients decreases as the cutoff point is moved downwards in the distribution. While the estimated coefficient for more concentrated markets is still slightly larger than the one for less concentrated markets when the sample is split at the median of HHI, there is no statistically significant difference among them anymore. Both estimated coefficients approach the value of the non-interacted slope in model A.

The upper quintile of the HHI distribution contains many industries that are often characterized as oligopolies such as automobiles, tobacco, milled grains (including cereals), agro-chemicals, and so forth. We believe these concentrated industries involve more intense strategic interaction and rivalry as described by Scott (2009). Under this interpretation, our empirical results are consistent with theoretical models that predict strategic interactions erode the option value of waiting (Grenadier 2002; Weeds 2002; Kulatilaka and Perotti 1998).[16] To our knowledge, our analysis is the first to empirically examine how the R&D investment–uncertainty relationship is influenced by strategic rivalry. The results are mixed in the literature studying the physical capital investment–uncertainty relationship (Bulan et al. 2009; Bulan 2005; Ghosal and Loungani 1996, 2000).

Some readers may be concerned that we use the dummy D(HHI > Q_{80}) instead of using ln(HHI) for the interaction term. We re-estimated the model using the dummy D(HHI > Q_{80}) as a independent regressor instead of using ln(HHI) which conforms to the usual specification when including an interaction term. The results reported above hold with the dummy D(HHI > Q_{80}) having a negative sign, but it is only statistically significant in the pooled model.

Furthermore, we also re-estimated the model investigating the effect of concentration at the lower tail compared to the upper tail of the distribution. We estimated one slope for the upper quintile of the HHI distribution, one for the lower quintile, and one for the remaining medium

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[16] Note that strategic interaction as we have measured it does not completely erode the option value of waiting as Grenadier's model predicts. Since the option value of waiting is still relatively large for high concentration markets,

concentration in between. The results are virtually the same as presented in model B in Table 2 (therefore we omit a detailed presentation). The reaction to uncertainty of firms in markets in the upper quintile of the market concentration is significantly lower from those in medium concentrated markets. The reaction in low concentrated markets is not different from the medium concentrated markets.

Model C examines how firm size influences the firm-level R&D investment-uncertainty relationship. Large firms respond less to market uncertainty than small firms. The Chi-squared test shows a statistically significant difference across the two groups. These results are not driven by financial constraints since we control for internal and external access to financial capital. Without the financial constraints argument used in the prior research such as Ghosal and Loungani (2000), it is likely that large firms possess greater flexibility in R&D investment than small firms. With the ability to utilize R&D assets across multiple projects, large firms have more valuable marginal operating options and these offset the effects of uncertainty as described by Pindyck (1988). However, our data are not rich enough to rule out other sources of flexibility associated with size such as economies of scope or portfolio effects. We explored the firm size effect further by estimating a separate slope coefficient for the group of smallest firms, that is, firms with less than 50 employees (details not presented in Tables). It turns out that these do not differ significantly from those firms with 50 to 499 employees, but the largest firms still react significantly less to uncertainty than the medium-sized firms.[17]

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our evidence appears to be more consistent with the model presented by Novy-Marx (2007). However, our empirical analysis is not a formal test of the differences between these models.

[17] We also estimated the model by replacing ln(EMP) with the LARGE FIRM dummy in the regressions to conform with the usual specification when using interaction terms. The coefficient of the dummy LARGE FIRM is positive and significant at the 1% level and the results concerning the uncertainty measures hold as reported in Table 2.

>>> **Insert Table 2 about here** <<<

We also calculated marginal effects for both models, that is, dE(Y|X)/dx. The estimated marginal effects at the mean of uncertainty amount to -1.61 and -2.71 for large versus small firms (significantly different at 1% level), and -1.94 and -2.68 for highly concentrated industries vs. others (different at 5% level). As these numbers are somewhat difficult to interpret economically, we illustrate the impact of uncertainty on R&D over the range of the uncertainty distribution in Figure 1. It can be seen that the slope of the curve (the marginal effect) is more negative for smaller firms and for firms in highly concentrated industries compared to their respective control groups over a large range of the distribution.

>>> **Insert Figure 1 about here** <<<

<u>Potential endogeneity of the new product market uncertainty</u>

To construct our proxy of firm-specific uncertainty, we used the coefficient of variation of the firm's new product sales in years prior to their current R&D investment decision. The basic idea is that managers who experienced high volatility in their new product sales will expect greater levels of uncertainty going forward, which is an adaptive expectations concept. This uncertainty may come from a variety of sources such as uncertainty about customer adoption, supply relationships, the competitive reaction of rivals, and so forth. In all likelihood, the volatility of past new product sales will capture some aspects of the firm's own decision processes in addition to the exogenous behavior of other agents in the market. To the extent that our proxy captures the firm’s own behavior, it might be endogenous because unobservable factors that influenced its past sales performance might carry forward to influence its current R&D decision.

To address this possibility we use an industry uncertainty measure for each firm based on every other firm in the industry except itself. Specifically, we use the average volatility of past new product sales from all other firms in the industry as an alternative uncertainty proxy and re-estimate the models reported in Table 2. This uncertainty measure is clearly predetermined, but it is also exogenous because uncertainty faced by other firms in the industry is not an individual firm decision variable. It will affect R&D investment to the extent that other firms in the same industry face similar sources of uncertainty in new product introduction.

The results using this alternative uncertainty proxy are reported in Table 3. (The new uncertainty variables are labeled with an “ALT” prefix for clarity.) As was found previously, Model A shows that uncertainty in the market for new products significantly reduces firm-level R&D. However, unlike earlier findings, uncertainty in established product markets is now significant and negatively related to current R&D investment. (Need to estimate using Bloom measure for old uncertainty and talk about this a little.)

Among the control variables in Table 3, industry-level uncertainty is still insignificant in all models estimated by either pooled or random-effects. Our proxy for firm risk preferences (PASTINNO) has the correct sign and is now strongly significant in all regression models. Also of note, the availability of internal financing (PASTPCM) is now consistently positive and significant in all regression models. The results for the other control variables are quite similar to those reported in Table 2.

Models B and C reexamine how strategic rivalry and firm size affect the relationship between uncertainty and R&D investment. Firms in high concentration industries, the upper quintile of the HHI distribution, continue to respond less to uncertainty than firms in less concentrated industries. It is also the case that large firms continue to respond less to market uncertainty than small firms. The Chi-squared tests reported at the bottom of Table 3 under Models B and C show statistically significant differences across the groups. Using the alternative uncertainty proxy, however, the results are stronger than previously found. The interaction term for firms in high concentration industries is not significant which suggests the value of pre-emption completely offsets the value of waiting. Also, large firms do not respond significantly to uncertainty, which is similar to Ghosal and Loungani's (2000) findings for physical capital based on US industry data.

5 Conclusions [under construction]

Research and development (R&D) expenditure is a form of investment because it produces new knowledge that is cumulative and contributes to innovation and productivity in future time periods. Models of physical capital investment are frequently used to understand the incentives that drive R&D investment (Hall and Hayashi 1989). However, most empirical work on R&D investment relies on a simple investment model that ignores the recent insights from real options models. Real options models incorporate the opportunities and costs of future investment and disinvestment and draw attention to potentially important influence of uncertainty on the incentives for investment. This paper uses these insights to augment the standard R&D investment model and empirically examine the R&D investment-uncertainty relationship based on a firm-level panel database. Among the findings are:

- Market uncertainty matters for R&D
- greater uncertainty in new product markets is negatively related current R&D investment
- strategic rivalry tends to erode the option value of waiting
- large firms react less to market uncertainty

There are a number of issues that remain for future research. First, we must emphasize that we study innovative firms in the manufacturing sector. One must be cautious and not generalize our findings to non-innovative firms or to other sectors like services or agriculture. At this point, more research is needed before valid generalization can be done. Second our measure of uncertainty is intuitively appealing but is based on prior firm experience. To be completely consistent with theory, one would like an explicitly forward-looking measure. Third, while our firm-level panel data make a significant step forward in the analysis of firm-specific uncertainty, the time series dimension of our data is not rich enough to model the dynamics of the R&D investment-uncertainty relationship. Fourth, other empirical measures that capture economies of scope at the firm-level would allow researchers to analyze the mechanisms driving down real options values for large firms in greater detail.

Appendix

Table A.1: Sample description by industry

Industry	Number of firm-year obs.	Avg. R&D (mil.DM)	Avg. employment	Avg. R&D/ (empl. in thsd.)
Food, Tobacco	164	0.23	188.63	0.86
Textiles, Clothing, Leather	149	0.38	315.31	1.19
Wood, Paper, Printing/Publishing, Furniture	317	1.19	300.25	1.35
Chemicals	254	17.82	851.98	10.08
Rubber, Plastics	268	0.64	212.61	2.90
Non-metallic mineral products	164	0.86	254.01	2.22
Metal production and processing	441	0.87	293.63	1.66
Machinery	489	4.63	446.12	5.39
ICT equipment, electronics	276	38.66	1262.78	9.02
Medical and precision instruments, optics	323	11.48	576.21	12.52
Vehicles	129	46.23	1118.63	7.31

Figure A.1: Scatter plot of demand uncertainty and new product sales uncertainty

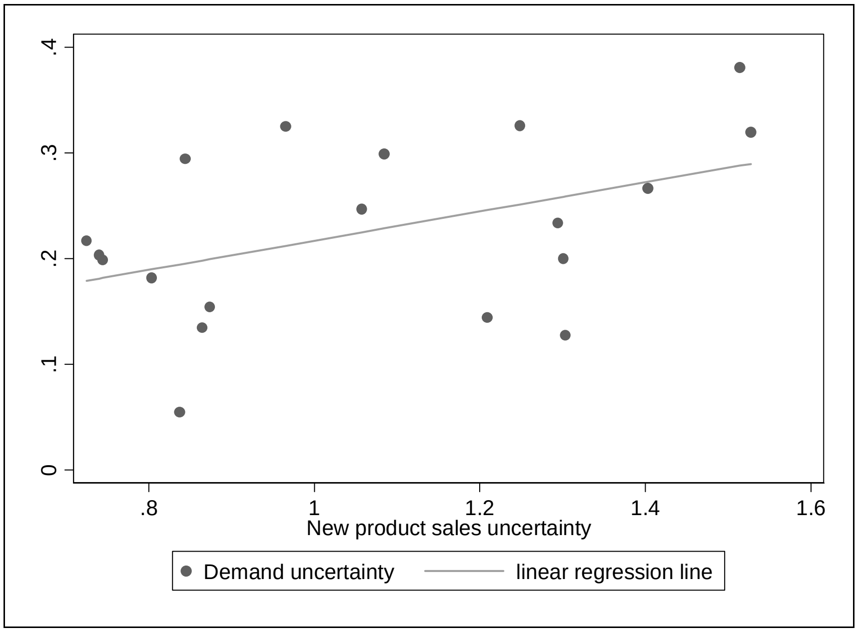

Figure A.2: Scatter plot of rivalry uncertainty and new product sales uncertainty

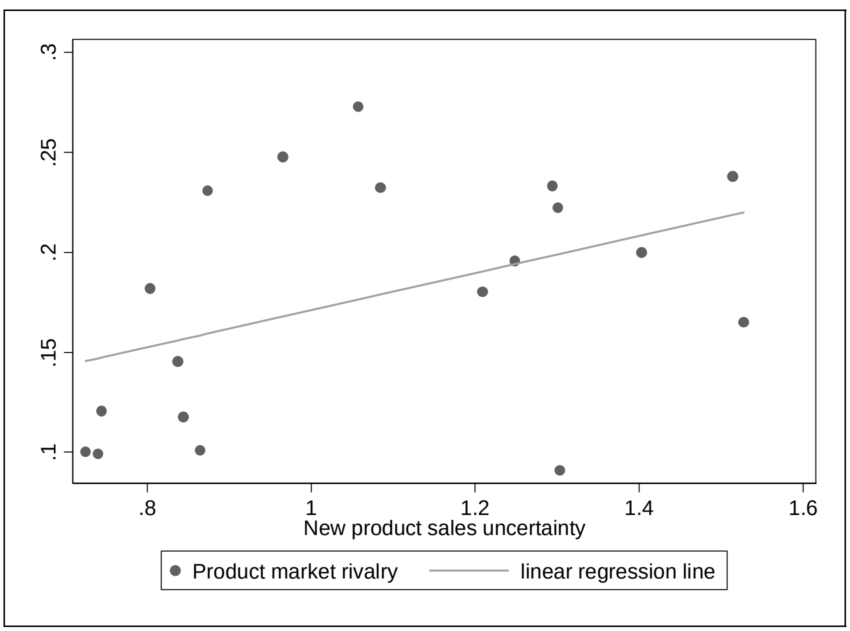

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Table 1: Descriptive Statistics (2974 firm-year observations)

Variable	Mean	Std. Dev.	Min	Max
$R\&D_{it}$	9.514	96.347	0	3000
$UNC\_NEW_{i,t-1}$	0.942	0.695	0.009	3
$UNC\_OLD_{i,t-1}$	0.510	0.371	0.011	2.449
$UNC\_IND_{i,t-1}$	0.118	0.105	0.009	1.067
$PASTINNO_{i,t-1}$	1.412	1.041	0.006	6.934
$PASTPCM_{i,t-1}$	0.275	0.139	-0.373	0.827
$EMP_{i,t-1}$	509.322	2493.741	1	45000
$PSTOCK_{i,t-1}/EMP_{i,t-1}$	0.018	0.044	0	0.370
$HHI_{i,t-1}$	48.379	71.485	3.213	1000
$RATING_{i,t-1}$	215.507	66.301	100	600
Large [$D(EMP_{i,t-1}>500)$]	0.145	0.352	0	1

Note: 10 industry dummies and 6 time dummies not shown.

Table 2: Tobit regressions of ln(R&D_{it}). 1995-2001. 2974 firm-year observations

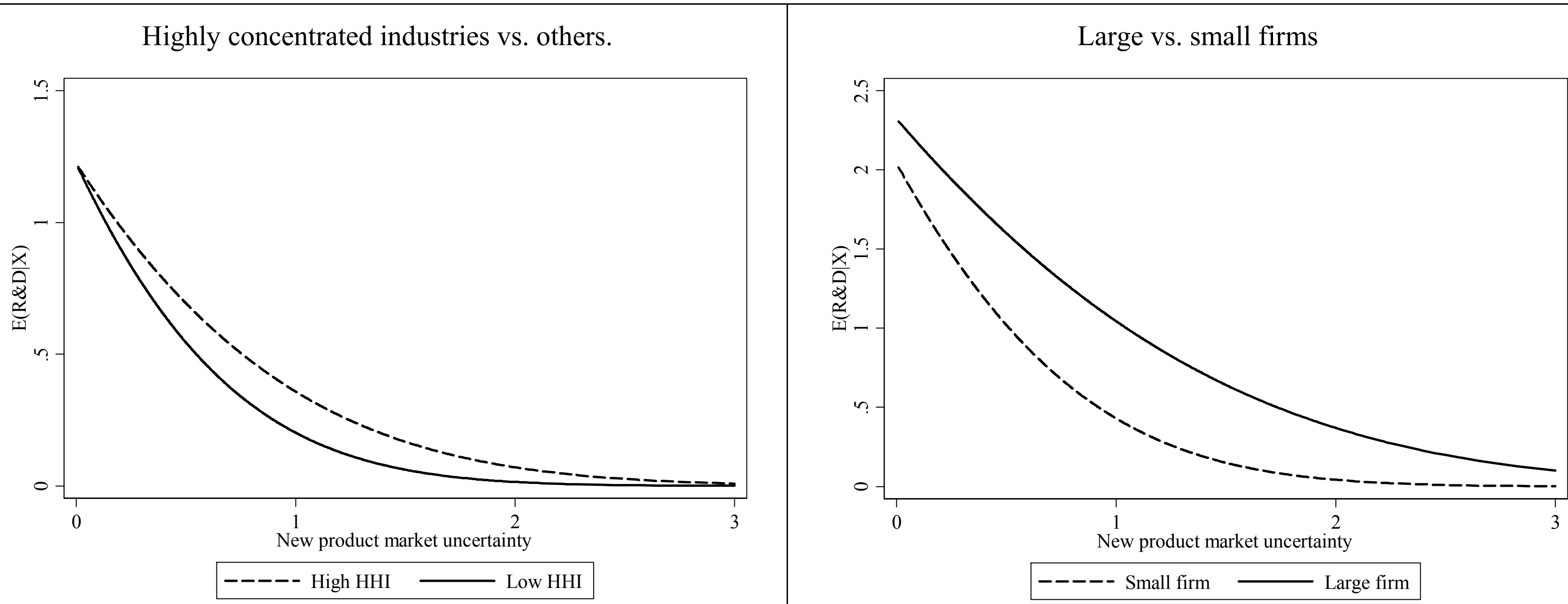
	Model A		Model B		Model C	
Variable	Pooled Tobit[a)]	RE Panel Tobit	Pooled Tobit[a)]	RE Panel Tobit	Pooled Tobit[a)]	RE Panel Tobit
$UNC\_NEW_{i,t-1}$	-4.346***	-3.333***				
	(0.298)	(0.277)				
$UNC\_NEW_{i,t-1}$ * D(HHI $_{i,t-1} > Q_{80}$)			-3.280***	-2.513***		
			(0.509)	(0.421)		
$UNC\_NEW_{i,t-1}$ * D(HHI $_{i,t-1} \leq Q_{80}$)			-4.537***	-3.486***		
			(0.299)	(0.284)		
$UNC\_NEW_{i,t-1}$ * LARGE FIRM					-2.717***	-1.650***
					(0.606)	(0.499)
$UNC\_NEW_{i,t-1}$ * SMALL FIRM					-4.582***	-3.577***
					(0.300)	(0.282)
$UNC\_OLD_{i,t-1}$	0.052	0.243	0.048	0.230	0.019	0.212
	(0.331)	(0.354)	(0.330)	(0.353)	(0.331)	(0.352)
$UNC\_IND_{i,t-1}$	0.478	0.732	0.389	0.625	-0.496	0.335
	(1.579)	(1.187)	(1.570)	(1.185)	(1.636)	(1.193)
$PASTINNO_{i,t-1}$	0.175	0.329*	0.190	0.337**	0.169	0.324
	(0.156)	(0.170)	(0.155)	(0.170)	(0.157)	(0.169)
$PASTPCM_{i,t-1}$	1.751*	1.068	1.830*	1.119	1.552	0.971
	(0.977)	(0.963)	(0.978)	(0.961)	(0.972)	(0.957)
$\ln(EMP_{i,t-1})$	1.420***	1.497***	1.431***	1.501***	1.220***	1.299***
	(0.097)	(0.097)	(0.097)	(0.098)	(0.106)	(0.109)
$PSTOCK_{i,t-1}/EMP_{i,t-1}$	8.886***	9.136***	8.872***	9.124***	8.611***	8.748***
	(2.041)	(2.607)	(2.053)	(2.602)	(2.040)	(2.592)
$\ln(HHI_{i,t-1})$	-0.124	0.023	-0.388**	-0.188	-0.139	0.003
	(0.147)	(0.138)	(0.167)	(0.160)	(0.144)	(0.137)
$\ln(RATING_{i,t-1})$	0.706	0.212	0.674	-0.189	0.852	0.326
	(0.572)	(0.506)	(0.573)	(0.505)	(0.565)	(0.503)
Intercept	-15.466***	-15.224***	-14.521***	-14.449***	-15.081***	-14.696***
	(3.636)	(3.114)	(3.636)	(3.121)	(3.583)	(3.098)

Table 2 continued

Joint significance of industry dummies ($\chi^2(10)$)	71.12***	94.22***	71.38***	93.76***	76.81***	99.85***
Joint significance of time dummies ($\chi^2(6)$)	123.02***	140.03***	123.43***	141.62***	121.69***	138.71***
Joint test on difference of slope coefficients of UNC_NEW variables ($\chi^2(1)$)			6.67***	6.62***	10.32***	16.64***
Log-Likelihood	-6169.88	-5963.15	-6162.24	-5959.88	-6154.74	-5954.91
McFadden-R^2	0.144	0.173	0.146	0.173	0.146	0.174

Note: Standard errors in parentheses. *** (**.*) indicate a significance level of 1% (5%. 10%).
a) Standard errors are clustered at the firm-level (881 clusters).

Figure 1: Estimated effects of new product market uncertainty on R&D investment



Note: High concentrated industries are above the upper quintile of the HHI distribution. All covariates except new product market uncertainty are taken at their median values. Unlike employment as shown in the right panel of this figure, HHI is not significant as covariate in the regression. Therefore we restricted its independent impact to zero for this illustration.

Note: Large firms have more than 500 employees. In order to draw this curve we used reference firms that have +/- 100 employees above or below the cutoff. i.e. the small firm has 400 employees and the large firm 600. All covariates except new product market uncertainty are taken at their median values.

Table 3: Tobit regressions of ln(R&D$_{it}$). 1995-2001. 2974 firm-year observations: Alternative Uncertainty Proxy

	Model A		Model B		Model C	
Variable	Pooled Tobit[a)]	RE Panel Tobit	Pooled Tobit[a)]	RE Panel Tobit	Pooled Tobit[a)]	RE Panel Tobit
ALT_UNC_NEW$_{i.t-1}$	-1.500***	-1.056***				
	(0.471)	(0.327)				
ALT_UNC_NEW$_{i.t-1}$ * D(HHI $_{i.t-1}$ > Q_{80})			-0.319	-0.406		
			(0.623)	(0.445)		
ALT_UNC_NEW$_{i.t-1}$ * D(HHI $_{i.t-1}$ ≤ Q_{80})			-1.922***	-1.313***		
			(0.479)	(0.349)		
ALT_UNC_NEW$_{i.t-1}$ * LARGE FIRM					-0.615	-0.176
					(0.616)	(0.481)
ALT_UNC_NEW$_{i.t-1}$ * SMALL FIRM					-1.746***	-1.303***
					(0.480)	(0.342)
ALT_UNC_OLD$_{i.t-1}$	-0.848**	-0.217	-0.932**	-0.259	-0.853**	-0.233
	(0.430)	(0.380)	(0.427)	(0.380)	(0.433)	(0.379)
UNC_IND$_{i.t-1}$	0.959	0.621	-1.000	0.494	-1.349	0.434
	(1.839)	(1.198)	(1.787)	(1.197)	(1.853)	(1.201)
PASTINNO$_{i.t-1}$	1.977***	1.530***	2.013***	1.552***	1.984***	1.534***
	(0.184)	(0.155)	(0.183)	(0.155)	(0.183)	(0.155)
PASTPCM$_{i.t-1}$	3.642***	1.934*	3.781***	2.015*	3.445***	1.828*
	(1.072)	(1.071)	(1.073)	(1.069)	(1.071)	(1.068)
ln(EMP$_{i.t-1}$)	1.805***	1.805***	1.800***	1.804***	1.646***	1.658***
	(0.107)	(0.107)	(0.106)	(0.107)	(0.130)	(0.122)
PSTOCK$_{i.t-1}$/EMP $_{i.t-1}$	14.800***	12.578***	14.524***	12.365***	14.596***	12.210***
	(2.606)	(2.798)	(2.585)	(2.794)	(2.687)	(2.794)
ln(HHI$_{i.t-1}$)	0.021	0.162	-0.379*	-0.071	0.004	0.145
	(0.171)	(0.152)	(0.227)	(0.186)	(0.171)	(0.152)
ln(RATING$_{i.t-1}$)	0.731	-0.103	0.686	0.089	0.859	0.208
	(0.609)	(0.540)	(0.613)	(0.540)	(0.607)	(0.540)
Intercept	-24.560***	-21.502***	-22.823***	-20.554***	-24.212***	-21.111***
	(3.838)	(3.286)	(3.874)	(3.310)	(3.831)	(3.279)

Table 3 continued

Joint significance of industry dummies ($\chi^2(10)$)	113.02***	137.48***	113.25***	135.73***	114.22***	137.87***
Joint significance of time dummies ($\chi^2(6)$)	126.49***	129.14***	126.42***	128.96***	126.01***	127.39***
Joint test on difference of slope coefficients of UNC_NEW variables ($\chi^2(1)$)			8.63***	4.63**	5.05**	6.18**
Log-Likelihood	-6385.83	-6022.79	-6378.32	-6020.48	-6380.12	-6019.71
McFadden-R^2	0.114	0.165	0.115	0.165	0.115	0.165

Note: Standard errors in parentheses. *** (**.*) indicate a significance level of 1% (5%. 10%).
a) Standard errors are clustered at the firm-level (881 clusters).