Patent Protection, Market Uncertainty, and R&D Investment[1]

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Abstract

Real options investment theory predicts current investment falls as uncertainty about market returns increases. In the case of R&D investment, which is usually considered an irreversible form of investment, this effect should be quite pronounced. This paper tests the real options prediction about the R&D investment–uncertainty relationship and further considers how patent protection influences this relationship. Patent protection, by limiting the threat of market rivalry, should mitigate firm-specific uncertainty and stimulate current R&D investment. Our empirical results support both the prediction of real options theory and the mitigating effect of patent protection.

Keywords: Real Options Theory, Uncertainty, R&D, Intellectual Property Protection, Censored Regression

JEL Classification: O31, O33, C25

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1 Introduction

The main reason governments grant patent protection is to spur innovation. Patents give inventors temporary monopoly rights that allow them to appropriate a greater share of the returns from their innovations and this augments private incentives to undertake research and development (R&D) investment. Consequently, patent protection should stimulate private R&D investment. However, the size of the R&D stimulus from patent protection is far from clear since it depends on how effective patents are as a mechanism for appropriating returns.

Drawing on real options investment theory, this paper highlights one mechanism through which patents may improve appropriability and stimulate R&D investment – by reducing the effect of market uncertainty on the firm's investment decision. The real options framework predicts that greater uncertainty about market revenues reduces investment in irreversible capital by increasing the value of waiting to invest (Pindyck 1991; Dixit 1992; Dixit and Pindyck 1994). R&D investment is highlighted in this literature as a particularly relevant example of irreversible capital since a large proportion of R&D supports the salaries of research personnel and cannot be recouped if projects fail. Firms can avoid large losses by waiting for new information about market conditions and forgoing investment when this information is unfavorable. This would lower current R&D investment. Alternatively, a patent may protect the firm from market competition due to, among other things, imitation by rivals. This reduces the patenting firm's perceived level of market uncertainty, decreases the value of waiting, and leads to greater current R&D investment.

In this paper, we undertake an empirical analysis to investigate the evidence supporting the real options investment theory and the interaction between uncertainty and patent protection for firm-level R&D investment. Specifically, we examine two questions. First, do firms reduce current R&D investment in response to higher perceived levels of market uncertainty as predicted by real options investment theory? Second, does patent protection mitigate the firm's response to market uncertainty? If patent protection mitigates market uncertainty, R&D investment by patenting firms should be less responsive to revenue volatility than non-patenting firms. Our regression analysis examines these hypotheses using panel data on innovative firms in Germany's manufacturing sector.

We find that firm-level R&D investment falls in response to higher levels of uncertainty as perceived through revenue volatility. Consistent with the orientation of R&D investment toward innovation, it is revenue volatility in the firm's new product markets that reduces R&D investment and not revenue volatility in the firm's established product markets. Moreover, we find that patent protection mitigates the influence of uncertainty. R&D investment by patenting firms is less responsive to revenue volatility in new product markets than R&D investment by non-patenting firms. Even among patenting firms, R&D investment by those firms holding more patents is less sensitive to uncertainty. Our models control for access to internal and external capital, non-diversifiable risk at the industry level, and a variety of other potential determinants of R&D investment. The panel data models account for firm specific effects that may influence investment such as firm-level risk aversion or unobserved heterogeneity in managerial practices.

The next section of the paper provides a brief review of the prior literature on the investment-uncertainty relationship. Section 3 discusses the data and measurement of uncertainty and other covariates. Our econometric approach and the results are presented in section 4 and concluding remarks appear in section 5.

2 Literature and Hypotheses

The relationship between investment and uncertainty is an important ongoing topic of research in both the theoretical and empirical literatures. In the theoretical literature, Abel et al. (1996) show that investment decisions involve the acquisition or exercise of "reversibility" and "expandability" options. The reversibility option captures the value of opportunities and costs associated with disinvestment at some point in the future. The reversibility option increases the incentive for current investment when future returns are uncertain since the firm acquires this option by purchasing capital. On the other hand, the expandability option captures the value of opportunities and costs associated with investment at some point in the future. This option decreases the incentive for current investment when future returns are uncertain since the firm acquires this option by delaying the purchase of capital. Since these options have offsetting effects on the incentive to invest, their model shows that the net effect of uncertainty on current investment is theoretically ambiguous. (Butzen and Fuss 2002, Carruth et al. 2000, Lensink et al. 2001 provide reviews of the theoretical and empirical literatures emphasizing physical capital investment.)

The type of the capital being considered for purchase will partly determine the nature of the options facing the firm and potentially resolve some of the theoretical ambiguity. For instance, research and development is typically considered in the literature as an investment that has no (or extremely small) reversibility option but has a significant expandability option. R&D investment is often characterized as completely irreversible (see, for instance, Dixit and Pindyck 1994, p. 424) since these expenditures are directed toward the salaries of research personnel and the purchase of task-specific equipment and materials. When irreversibility is combined with uncertainty over future returns and the opportunity to delay investment, only a positive expandability option exists and this implies the optimal investment trigger is greater than the trigger given by the traditional net present value rule. Since the value of the expandability option increases in the level of uncertainty, the incentive for current investment is lower at higher levels of uncertainty. This suggests a negative relationship between the current level of R&D investment and uncertainty.[2]

The type of capital investment also influences the nature of the uncertainty relevant to the investment decision. Private R&D is generally regarded as investment in knowledge producing activities aimed at the discovery and introduction into use of new products and processes. Uncertainty about future market returns to innovation will play a critical role in the decision to invest in R&D.[3] For instance, when new products are introduced into the marketplace, firms are uncertain about the acceptance by potential customers, the reliability of suppliers and production operations, and the reaction by rival firms. When these uncertainties are high, expandability options suggest R&D investment will be delayed. This leads to our first hypothesis.[4]

H1: The level of current R&D investment falls as the degree of uncertainty about returns to innovation increases.

One of the most significant sources of uncertainty about the returns to innovation is the competitive reaction upon introduction into the marketplace. While there are a variety of actions firms may take to reduce competitive uncertainty, obtaining legal protection through

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[2] Subsequent theoretical research has explored issues related to the firm's opportunity to delay investment. When investment has strategic value, Kulatilaka and Perotti (1998) show the value of growth options increase with the level of uncertainty and offset (at least partially) the affect of expandability options on the incentive for current investment. Weeds (2002) considers a real options model with R&D competition and finds equilibrium outcome depends on the balance between the value of delay and the expected benefit of pre-emption. In a recent contribution, Novy-Marx (2007) finds that investment decisions are delayed in a perfectly competitive market when firm-level opportunity costs and heterogeneity are important.

[3] Pindyck (1993) presents an alternative model with uncertainty about costs. He finds that higher technical uncertainty leads to earlier investment while higher input cost uncertainty leads firms to delay investment.

[4] Our literature search identified two prior studies examining the relationship between R&D investment and uncertainty. Goel and Ram (2001) examine a panel of OECD countries and measure uncertainty using the standard deviation of each country's inflation rate. They find that uncertainty reduces the share of R&D in GDP. Minton and Schrand (1999) find that cash flow volatility is associated with lower levels of R&D investment using a sample of public companies drawn from Compustat.

the patent system figures prominently.[5] By obtaining a patent firms prevent current and potential competitors from selling an imitation of their innovation which protects their revenue stream from business stealing effects. The idea that patent protection increases a firm's ability to appropriate the returns from their innovations is commonplace in the literature. The question that has received the most attention is how effective patent protection is as a means for appropriating returns.[6] To the degree that patent protection is effective, obtaining a patent should reduce the effect of market uncertainty on the firm's R&D investment. This leads to our second hypothesis.

H2: Patent protection mitigates the effect of uncertainty about the returns to innovation and increases the level of current R&D investment.

3 Empirical Set-up and Data

3.1 Set-up

As outlined above we are interested in the relationship of R&D investment and market uncertainty and how patent protection may influence this relationship. Thus, we estimate a model of the form

$$(1)\ \text{R\&D} = f\left(\text{Uncertainty}, \text{Patenting}, \text{Uncertainty}{\times}\text{Patenting}, \text{Systematic Unc.}, \text{Controls}\right)$$

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[5] Mazzoleni and Nelson (1998) discuss the various economic theories for patent protection and review some of the early empirical literature.

[6] This observation is the starting point for a large theoretical and empirical literature that cannot be summarized in this paper. The empirical literature uses either survey data or patent renewal data to shed light on differences in patent effectiveness or patent value (see, for instance, Pakes 1986). The literature examining the relation between patents and firm value is surveyed in Czarnitzki et al. (2006). Also, since patenting involves the disclosure of information, the firm's decision to patent represents a tradeoff between monopoly rents and disclosure. Thus, patents do not unambiguously induce R&D investment. Arora et al. (2007) discuss this issue and Cohen (2005) surveys the arguments and evidence on appropriation.

In equation (1), hypothesis one predicts that firm-specific uncertainty about future market returns reduces investment. The interaction term between uncertainty and patenting is used to test hypothesis two. A positive and significant coefficient on this term shows that firms with patents perceive less uncertainty about future market returns and invest more in current R&D investment. Patenting, which is the firm's patent stock, is a control variable in this analysis, but it is shown explicitly in equation (1) to highlight that we control for firm-level innovative "capabilities" which are typically associated with growth options (Kulatilaka and Perotti 1998). Likewise, we explicitly show non-diversifiable (or systematic) market uncertainty at the industry level in equation (1) to highlight that a CAPM type influence of uncertainty on investment is held constant.

One important component of our empirical model is the measure of firm-specific uncertainty about future market returns to innovation. As mentioned in the last section, firms may perceive uncertainty about market returns along a number of dimensions. To be completely consistent with theory, one would like a forward-looking measure of firm-specific uncertainty.[7] Because past experience is one of the most important mechanisms for learning, a reasonable proxy can be constructed based on the firm's past market experience as innovators. We use revenue volatility from past market introductions as our proxy for firm-specific uncertainty. Consequently, we assume that past market experience is informative about how firms perceive uncertainty going forward. Their market experience as innovators, however, is not the same as their market experience with established products, which rely on more stable demand and supply relationships. Thus, we generate two firm-specific

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[7] In the empirical literature studying the relationship between investment in physical capital and uncertainty researchers have used a variety of measures, each with their own strengths and weaknesses. Carruth et al. 2000 and Lensink et al. 2001 review these. Following Leahy and Whited (1996), three recent studies use stock market volatility measures of uncertainty for publicly traded firms (Baum et al. (2007), Bloom et al. (2007), Bulan (2005)). Most of our firms are privately owned and not traded in the public market. Consequently, this type of uncertainty proxy is not possible in our context.

uncertainty measures using the coefficient of variation of past sales revenue, one capturing uncertainty related to innovation (UNC_NEW) and the other capturing uncertainty related to established products (UNC_OLD). This allows for two separate sources of uncertainty to affect R&D investment.

Our uncertainty measures are calculated as coefficients of variation of past sales revenues at the firm level. In order to adjust sale volume for firm size effects, we rescale past sales revenues by the number of employees. The number of observations available for calculating the coefficients of variation for each firm depends on available pre-sample data for which we have three to nine years available (s = 1,…,S, with S ranging between 3 and 9):

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

where R denotes the volume of new or established product sales of firm i in year t and L refers to the number of employees.

3.2 Data

Our main data source is the Mannheim Innovation Panel (MIP), which is a business survey conducted by the Centre for European Economic Research (ZEW), Mannheim (Germany) since 1992. In addition to the survey data, we collected information on the patenting activity from the German Patent and Trademark Office. This database covers all German (including EPO priority applications with German coverage) since 1978. Finally, we use credit rating information from Creditreform (the largest German credit rating agency) to gauge firm-level access to external financial capital, a control for potential financial constraints.

In our study we are able to use panel data from 1995 to 2001 from the MIP survey. The earlier years from 1992 and 1994 are needed to calculate lagged variables such as the uncertainty measures and the control variables described below. As our main uncertainty measure is derived from new product introductions, we base our analysis on product innovators in the manufacturing sector. An innovative firm is defined to be a company that introduced at least one new product in the past. The phrase "in the past" refers to the pre-sample period (3 to 9 years) which is used to generate our empirical proxies before the firm enters our panel database as an observation.

The database for our empirical analysis is constructed from firm-year observations. For example, suppose the dependent variable (R&D investment) is observed in 2001. Because we require past information on new product sales to generate our uncertainty measure, the firms must be observed as a product innovator in the past. Due to the fact that the MIP is based on a survey, firms do not always respond in every year so that the panel structure is unbalanced. We require that the firm is observed at least three times before the corresponding year *t*. If that applies, we calculate our uncertainty measures as described above (coefficient of variation of new product sales and established product sales). This procedure is applied for every firm-year and leads to a final sample of 2,947 observations corresponding to 881 different product innovator firms. The panel structure is unbalanced: 21% of firms are only observed twice, 23% three times, another 21% four times, and the remaining 36% are observed between 5 and 7 times. Note that we performed robustness tests of the regressions presented below by restricting the time window used for the calculation of historical variables from three to six years. This did not affect any of the findings we present in the next section. Hence, we do not present results from these regressions.

The dependent variable is R&D expenditure at the firm level (RD_i) in millions of "Deutsche Mark" DM (1.95583 DM = 1 EUR). Although we consider only previous product innovators, we find that about one third of the firm-year observations on R&D have a value of zero. This is due to the fact that our sample contains many small firms that might conduct R&D only intermittently (the median number of employees per firm in our sample is 110). It is also possible, however, that these firms choose not to invest in R&D because of uncertainty about their future market revenues, which is consistent with the predictions from real options theory (see, for instance, the discussion of hysteresis in Dixit, 1992). Our econometric analysis takes this into account by modeling the censored distribution of R&D. Above zero, the distribution of R&D spending is quite skewed and this motivates our logarithmic specification ($\ln R\&D_i$). Since we cannot take the log of the censored observations at $R\&D_i = 0$, we set those observations to the minimum observed positive R&D value in the sample and interpret this observed minimum as the censoring point in the regression models.

The capital asset pricing model (CAPM) suggests a negative relationship between non-diversifiable or systematic uncertainty and firm-level investment to the extent that firm-level returns are correlated with aggregate volatility. Since our sample has a large proportion of private firms, we cannot follow the standard approach of calculating firm specific "betas" and constructing a proxy of systematic uncertainty. As an alternative, we generate an uncertainty measure at the 3-digit NACE industry level from official statistics from the German government. We calculate the coefficient of variation for total industry sales (UNC_IND_{it-1}).[8] This is included in our regressions as a control for aggregate systematic uncertainty that could influence firm-level R&D investment. We also have annual time dummy variables in all regressions to account for macroeconomic shocks affecting R&D investment.

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[8] NACE is the European standard industry classification. As we do not have information about employment at this detailed industry level, we do not normalize industry sales by the number of employees, but the number of firms active in that industry in a given year.

Another potential confounder in the relationship between investment and uncertainty is the risk aversion of the firm. If firms are risk-averse, then investment is expected to fall as uncertainty increases. To control for this possibility, we observe that each firm's risk preferences should be strongly reflected in its recent innovation strategy. That is, firms with an aggressive product innovation strategy should be the *least* risk-averse firms, while those following a conservative innovation strategy should be the most risk-averse. We include a control variable in the analysis for the firm's relative innovativeness in its industry. 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). In addition, the firm-specific effect in the panel data models should also control for risk preferences to the extent these are time constant in our sample period.

To control for firm-level innovation capabilities we use the firm's lagged patent stock, $PSTOCK_{it-1}$, where this is calculated from the patent database for each firm since 1978 using a 15% annual obsolescence rate of knowledge (see e.g. Griliches and Mairesse, 1984, or Hall, 1990, for details). As mentioned above, it controls for a firm's prior patenting success and R&D capabilities which are expected to stimulate current R&D investment due to either productivity differences or perceived grow options.

To test hypothesis two, we use a patent dummy variable interacted with uncertainty. This variable, called $D(PSTOCK_{i,t-1}>0)$, identifies firms with patent protection in the pre-sample period. It captures differences between the group of patenting firms and non-patenting firms in their perception of the influence of uncertainty on R&D investment. In the results section, we also present regressions using different percentiles of the patent distribution as a robustness check since one might be concerned that selection into patenting in the past somehow reflects unobserved differences between patenting and non-patenting firm. The firm-specific effects in the panel models should also help alleviate concerns about unobserved heterogeneity.

Market type and the degree of competition may also influence the firm's investment decision. We control for market type using ten industry dummy variables. To measure the degree of competition, we include each market's seller concentration using the Herfindahl index based on shares of total market sales at the 3-digit NACE level, ln(*HHI*).[9]

With regard to other firm characteristics, we include controls for firm size and liquidity constraints. The number of employees controls for heterogeneity in size with respect to the propensity to conduct R&D. We include two controls for potential liquidity constraints. For access to external capital, we use the firm's credit rating, ln(*RATING*), lagged one period.[10] The rating is an index ranging from 100 to 600, where 600 is the worst and essentially corresponds to bankruptcy of the firm. For the availability of internal capital, we use a measure of the firm's average price-cost margin, (*PASTPCM*), in the pre-sample period:[11]

$$(3) \qquad PASTPCM_{i,t-1} = \frac{1}{S}\sum_{s=1}^{S} PCM_{i,t-s}$$

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

where the pre-sample period corresponds to the period used for the uncertainty measure.

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[9] As alternative measure for market power, we also used the market share on the 3-digit NACE industry level. As the results never changed, we omit a detailed presentation of regressions using market share instead of the Hefindahl index.

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

[11] 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 invested 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).

Furthermore, we include a location dummy, EAST$_i$, indicating that the firm is based in Eastern Germany. These firms may show different investment behavior, on average, due to the German re-unification in 1990. All else constant, such firms may be able to invest more into R&D than Western German firms, as the federal government maintained several support programs for investment during the 1990s and early 2000s in order to foster the catching-up process of the former German Democratic Republic economy. Finally, six time dummies absorb macroeconomic shocks that could have affected R&D investment decisions during the period under review. Table 1 presents descriptive statistics of all variables used. 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 <<<

4 Estimation Method and Results

We employ two different models with our panel data, a pooled cross-sectional approach and a random effects panel estimator. The model can be written as

$$\begin{aligned} & y_{it} = \max\left(0, x_{it}\beta + c_i + u_{it}\right), \quad i = 1,2,\ldots,N, \ \ t = 1,2,\ldots,T \\ & u_{it} \mid x_i, c_i \sim N\left(0, \sigma_u^2\right) \end{aligned} \tag{4}$$

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. We estimate two versions of this model. 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 is not necessary to 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 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 so that $c_i \neq 0$. Consistency of the random effects model requires the strict exogeneity assumption, that is, the error term has 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 panel specification as superior to the pooled cross-sectional results. Rather think of it as a robustness check allowing for unobserved firm-specific effects at the cost of more restrictive assumptions otherwise. Note that we keep the time-invariant regressors (EAST and industry dummies) in the random-effects panel model in order to reduce the error variance of the firm-specific effect.

Table 2 presents our regression results. We consider two versions of the empirical specification: model A excludes the interaction between market uncertainty and patent protection in order to test the idea that market uncertainty reduces R&D investment (hypothesis one). Model B includes the interaction covariate to test hypothesis two that patenting mitigates the effect of uncertainty and leads to greater current R&D investment.

As predicted by real options theory, model A shows that uncertainty about market returns significantly reduces firm-level R&D investment. This finding is consistent with prior work on R&D and a larger body of empirical findings on how uncertainty effects physical capital investment. [12] In our analysis, we can distinguish uncertainty as perceived from new versus established product markets. While both variables show a negative sign as

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[12] See Goel and Ram (2001), Minton and Schrand (1999) and the references in footnote 7.

expected, it turns out that that the effect of uncertainty in established product markets is not significantly different from zero. The effect of uncertainty in new markets, however, is highly statistically significant in both the pooled cross-sectional and the panel models.

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

For the control variables in model A, our proxy for systematic risk (UNC_IND) has no significant effect. This suggests that the CAPM mechanism is not an important determinant of R&D investment, although the time dummy variables are significant that these could be capturing the effect of systematic uncertainty. Even though there appear to be no prior studies of R&D investment to corroborate this result, Leahy and Whited (1996) did not find evidence supporting a CAPM effect nor did Bulan (2005) find market or industry uncertainty significant for determining irreversible physical investment. Our control for firm-level risk preferences (PASTINNO) is significant and shows the expected sign – R&D investment increases as firms pursue more aggressive innovation strategies. The availability of internal finance (PASTPCM) increases R&D investment, however, access to external financing (ln(RATING)) is not significant. PASTPCM, however, is not significant in the random effects panel models because this variable has little variation over time. Larger firms invest more in R&D and firms with better R&D capabilities invest more. Both the industry dummies reflecting differences in investment across market types and the time dummies are jointly significant in all regressions. The EAST dummy is positively significant suggesting that firms in the Eastern part of Germany invested more – all else constant – during the late

1990s and early 2000s. As outlined above, this may be due to government support programs.[13]

Model B allows the effect of uncertainty on R&D investment to differ across patenting and non-patenting firms. The interaction variable is positive and significant. This shows that R&D investment by patenting firms is less sensitive to uncertainty in new product markets than non-patenting firms. Patenting, however, does not completely offset the influence of uncertainty on R&D investment. This is expected since patent protection reduces perceived uncertainty about competitive rivalry but does not address other forms of uncertainty that might be important such as customer acceptance or supplier and production shocks.[14,15]

In order to evaluate the magnitude of the estimated uncertainty effects, we calculate marginal effects using the change in the expected value of $Y_{it} = \ln(R\&D_{it})$ (see Greene, 2003: 764, for E(Y|X) in the Tobit model). As our model is formulated in terms of log of R&D investment, the difference in expected values approximates the growth in R&D upon a change in uncertainty:

$$(5) \qquad E\left[Y \mid X, UNC\_NEW + 10\%\right] - E\left[Y \mid X, UNC\_NEW\right] = -0.26 .$$

Using the model, a 10% increase in uncertainty (taken from the median value of the covariates) leads firm to reduce R&D investment by 26%, a sizable impact.

Schankerman (1998) suggests calculating the “equivalent subsidy rate” (ESR) as a measure of the private value of patent rights. ESR answers the question: “If patent protection

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[13] The results for the control variables in model B are essentially the same. To save space, we will not discuss them separately.

[14] Using OECD data, Kanwar and Evanson (2003) find that intellectual property rights significantly increase R&D investment as a share of gross national product.

were eliminated, what cash subsidy would have to be paid to firms performing R&D to yield the same level of R&D?" (Schankerman 1998, p. 95). Using the estimates from model B, we conduct a slightly different counter-factual exercise: if a non-patenting firm responded to uncertainty like a firm with patent protection (all else constant), what is the implied percentage increase in R&D investment?[16] This exercise suggests that patent protection confers a 43% increase in R&D investment. Figure 1 illustrates the difference in expected R&D investment as uncertainty increases between patenting and non-patenting firms (all covariates calculated at the median). While simple, our 43% ESR estimate for German firms is not out of line with other ERS estimates based on completely different methods. Using patent renewal data, Lanjouw (1998) shows simulation results for four West German technology groups. Her ESR estimates range from 11.5% for engines to 75.4% for textiles.[17]

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

Robustness tests

One may be concerned that unobserved differences between patenting and non-patenting firms are driving our results regarding the mitigating effect of patent protection on the firm's R&D response to uncertainty. As a robustness check, we split the firms in the sample into four groups. Rather than considering only patenting and non-patenting firms and

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[15] We tested for industry differences in the slope response to uncertainty. Using a Chi-squared test, we could not reject the null hypothesis of equality across the industry coefficients.

[16] The calculation is analogous to equation (5), but instead of using a 10% of uncertainty, we calculate the difference in the state of patenting vs. non-patenting using a median firm, all else constant.

[17] Schankerman (1998) discusses a variety of ERS estimates found using patent renewal data. There appear to be fairly substantial differences across countries and technology fields. We present an estimate for an "median" manufacturing firm in Germany between 1995 and 2001.

the difference in their reaction to new product market uncertainty, we now estimate four different slope coefficients for uncertainty. The first group refers to non-patenting firms (similar to the dummy variable used above):

Group 1: PS0_UNC_NEW = UNC_NEW * D(PSTOCK/EMP =0).

Now, however, we split the patenting firms into three evenly distributed groups according to the quantiles of the patent stock distribution. We estimate three slopes for firms that have a low, medium and high patent stock per employee, respectively. Let Q_{33} (Q_{67}) represent the 33% (67%) quantile of the observations with positive patent stocks.

Group 2: PSLOW_UNC_NEW = UNC_NEW * D(PSTOCK/EMP>0) * D(PSTOCK/EMP <Q_{33})
Group 3: PSMED_UNC_NEW = UNC_NEW * D(PSTOCK/EMP >0) * D(PSTOCK/EMP >Q_{33})
* D(PSTOCK/EMP <Q_{67})
Group 4: PSHIGH_UNC_NEW = UNC_NEW * D(PSTOCK/EMP >0) * D(PSTOCK/EMP >Q_{67})

The rest of the model is analogous to the previous regressions and the results are presented in Table 3. We find that the estimated slope coefficients for these new interaction variables decrease monotonically with increasing patent stocks per employee, that is, the more patents a firm holds (relative to its size) the less it responds to product market uncertainty. A joint test on systematic differences of the four slope coefficients clearly rejects the null hypothesis of equality (see bottom of Table 3). Therefore, we are confident that our earlier finding was not due to any self-selection effect into the patenting group. It turns out that even the size of the patent stock held has an impact on the firm's sensitivity to new product market uncertainty.

>>> Insert Table 3 about here <<<

As further robustness check, we estimated heteroscedastic models where the variance had been modelled group-wise multiplicatively (see e.g. Greene, 2003: 769). We included the 10 industry dummies and 5 size class dummies (based on employment) in the heteroscedasticity term. Although the estimations indicate weak heteroscedasticity, none of the results mentioned above changed. Therefore, we do not present these estimations in detail.

We also examined the broader measure of uncertainty: the variation in firms' total sales. However, it was never significant in any regression. This motivated the split into old and new product sales volatility. In the literature, scholars often use the standard deviation of firms total sales (or standard deviations of similar measures) over time. We estimated all models using standard deviations rather than coefficients of variations for the uncertainty measures. The results were basically the same. Using the coefficients of variation was simply motivated by reduced collinearity among the uncertainty measures.

5 Conclusions

This paper examines the how uncertainty about future market returns to innovation influences current R&D investment and how this influence is affected by patent protection. We highlight one mechanism through which patent protection may improve appropriability and stimulate R&D investment: patent protection reduces the firm's sensitivity to market uncertainty, decreases the value of waiting, and leads to greater current R&D investment. Our results show that higher levels of uncertainty reduce current R&D investment with the median firm in the German manufacturing sector reducing R&D investment by 26% in response to a 10% increase in uncertainty, on average. However, consistent with a real options mechanism patent protection offsets the firm's sensitivity to uncertainty and leads to greater current R&D investment. Our estimates suggest the *ex post* private value of patent rights for a median firm in our sample is about 43%, which is in line with prior estimates for Germany by Lanjouw (1998) using completely different data and methods.

As research progresses in this area, it would be beneficial to explicitly model the relationship between the usage of intellectual property rights and different forms of uncertainty faced by the firm. Due to data limitations, we are not able to investigate this deeply in our setting. It would be necessary to have long time-series data to calculate uncertainty measures and analyze how these interact with the decision to patent and how the effectiveness of patenting relates to the reduction of expected market uncertainty. We show that the sensitivity to uncertainty is reduced the more patents a firm holds, but we are not able to investigate strategic motives for patenting nor how multiple patents held by a firm interact with each other. For instance, it would be interesting to incorporate issues related to patent thickets or fencing in more detail. Furthermore, our uncertainty measures are generated from historical data. While it is reasonable to believe that firms build expectations upon past experience, it would be desirable to have an explicitly forward-looking perception of uncertainty.

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Table 1: Descriptive Statistics (2974 firm-year observations, 881 firms)

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
$PASTINNO_{i,t-1}$	38.778	25.652	0.125	99.167
$PASTPCM_{i,t-1}$	0.275	0.139	-0.373	0.827
$EMP_{i,t-1}$	509.322	2493.741	1	45000
$D(PSTOCK_{i,t-1}>0)$	0.431	0.495	0	1
$PSTOCK_{i,t-1}/EMP_{i,t-1}$	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
$EAST_i$	0.375	0.484	0	1

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

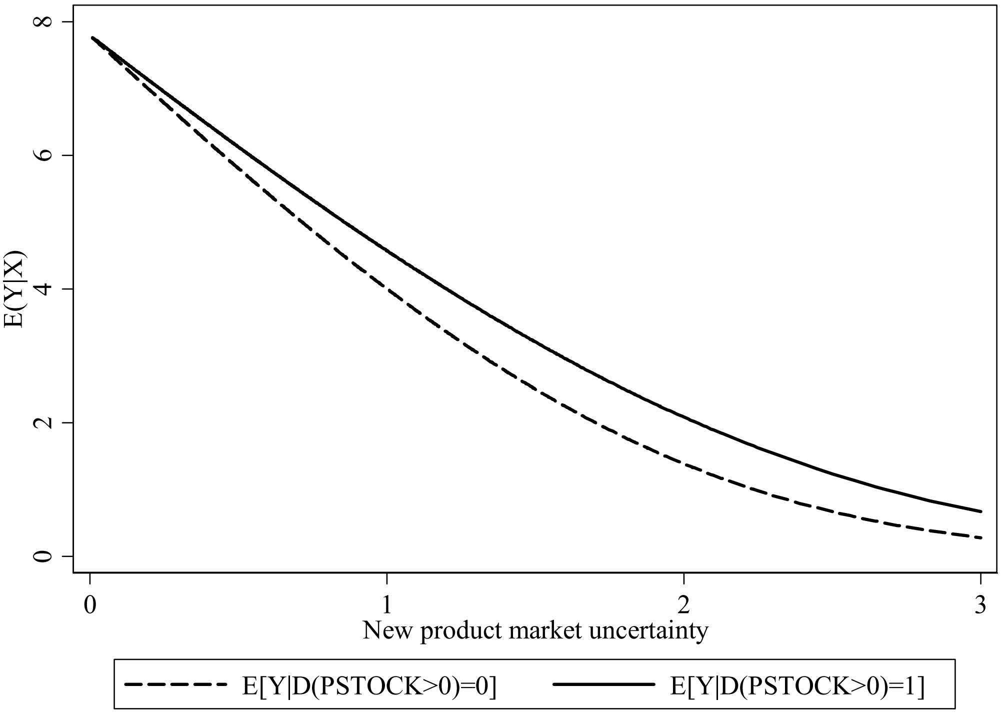
Table 2: Tobit regressions on ln(R&D$_{it}$), 1995-2001, 2974 firm-year observations

	Model A		Model B	
Variable	Pooled Cross-Sectional Tobit$^{a)}$	Random-Effects Panel Tobit	Pooled Cross-Sectional Tobit$^{a)}$	Random-Effects Panel Tobit
UNC_NEW$_{i,t-1}$	-4.106***	-3.055***	-4.273***	-3.291***
	(0.334)	(0.314)	(0.350)	(0.319)
UNC_NEW$_{i,t-1}$			0.710**	1.013***
* D(PSTOCK $_{i,t-1}$>0)			(0.355)	(0.279)
UNC_OLD$_{i,t-1}$	-0.659	-0.458	-0.708	-0.510
	(0.421)	(0.427)	(0.420)	(0.427)
UNC_IND$_{i,t-1}$	0.356	0.652	0.240	0.597
	(1.554)	(1.169)	(1.547)	(1.169)
PASTINNO$_{i,t-1}$	0.017*	0.025***	0.018**	0.028***
	(0.009)	(0.009)	(0.009)	(0.009)
PASTPCM$_{i,t-1}$	1.931**	1.220	2.008**	1.315
	(0.971)	(0.971)	(0.963)	(0.976)
ln(EMP $_{i,t-1}$)	1.458***	1.533)***	1.398***	1.448***
	(0.098)	(0.100)	(0.102)	(0.102)
PSTOCK $_{i,t-1}$/EMP$_{i,t-1}$	9.579***	9.426***	7.750***	7.037***
	(2.024)	(2.657)	(2.100)	(2.726)
ln(HHI$_{i,t-1}$)	-0.135	-0.009	-0.144	-0.030
	(0.145)	(0.137)	(0.146)	(0.137)
ln(RATING $_{i,t-1}$)	0.228	-0.207	0.221	-0.182
	(0.599)	(0.520)	(0.597)	(0.516)
EAST$_i$	0.849***	0.887***	0.886***	0.960***
	(0.325)	(0.317)	(0.325)	(0.318)
Intercept	-13.883***	-13.699***	-13.483***	-13.264***
	(3.678)	(3.086)	(3.670)	(3.064)
Joint significance of industry dummies ($\chi^2(10)$)	76.67***	93.95***	71.26***	87.15***
Joint significance of time dummies ($\chi^2(6)$)	122.56***	135.29***	121.15***	137.47***
Log-Likelihood	-6160.16	-5956.43	-6154.64	-5949.79
McFadden-R^2	0.146	0.174	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 uncertainty on R&D



Note: all other covariates are measured at the median.

Table 3: Tobit regressions on ln(R&D$_{it}$), 1995-2001, 2974 firm-year observations

Variable	Pooled Cross-Sectional Tobit[a)]	Random-Effects Panel Tobit
PS0_UNC_NEW$_{i,t-1}$	-4.202***	-3.265***
	(0.346)	(0.319)
PSLOW_UNC_NEW$_{i,t-1}$	-3.895***	-2.500***
	(0.519)	(0.414)
PSMED_UNC_NEW$_{i,t-1}$	-3.099***	-2.036***
	(0.515)	(0.453)
PSHIGH_UNC_NEW$_{i,t-1}$	-2.744***	-1.883***
	(0.610)	(0.606)
UNC_OLD$_{i,t-1}$	-0.771*	-0.532
	(0.419)	(0.427)
UNC_IND$_{i,t-1}$	0.463	0.598
	(1.519)	(1.181)
PASTINNO$_{i,t-1}$	0.020**	0.028***
	(0.009)	(0.009)
PASTPCM$_{i,t-1}$	2.004**	1.322
	(0.960)	(0.975)
ln(EMP$_{i,t-1}$)	1.411***	1.458***
	(0.101)	(0.102)
PSTOCK$_{i,t-1}$/EMP$_{i,t-1}$	5.029**	5.784*
	(2.199)	(3.122)
ln(HHI$_{i,t-1}$)	-0.153	-0.032
	(0.146)	(0.137)
ln(RATING$_{i,t-1}$)	0.132	-0.204
	(0.593)	(0.517)
EAST$_i$	0.885***	0.958***
	(0.324)	(0.316)
Intercept	-12.916***	-13.178***
	(3.679)	(3.098)
Joint significance of industry dummies ($\chi^2(10)$)	70.59***	86.17***
Joint significance of time dummies ($\chi^2(6)$)	118.84***	136.46***
Joint test on difference of slope coefficients of UNC_NEW ($\chi^2(4)$)	10.31**	15.13***
Log-Likelihood	-6150.66	-5948.90
McFadden-R^2	0.147	0.175

Note: Standard errors in parentheses. *** (**,*) indicate a significance level of 1% (5%, 10%).

a) Standard errors are clustered at the firm-level (881 clusters).

Table 4: Correlation Matrix

	ln(R&D$_{it}$)	UNC_NEW$_{i,t-1}$	UNC_OLD$_{i,t-1}$	UNC_IND$_{i,t-1}$	PASTINNO$_{i,t-1}$	PASTPCM$_{i,t-1}$	ln(EMP $_{i,t-1}$)	PSTOCK $_{i,t-1}$ /EMP$_{i,t-1}$	ln(HHI$_{i,t-1}$)	ln(RATING$_{i,t-1}$)
ln(R&D$_{it}$)	1.0000									
UNC_NEW$_{i,t-1}$	-0.5836	1.0000								
UNC_OLD$_{i,t-1}$	0.0991	-0.2351	1.0000							
UNC_IND$_{i,t-1}$	0.1151	-0.0295	0.0360	1.0000						
PASTINNO$_{i,t-1}$	0.2613	-0.5703	0.5045	-0.0434	1.0000					
PASTPCM$_{i,t-1}$	0.0646	-0.1093	0.0253	0.0407	0.0793	1.0000				
ln(EMP $_{i,t-1}$)	0.4907	-0.2908	-0.0589	0.0799	0.0807	-0.0930	1.0000			
PSTOCK $_{i,t-1}$/EMP$_{i,t-1}$	0.2077	-0.2010	0.0399	0.0299	0.0436	0.0916	0.0364	1.0000		
ln(HHI$_{i,t-1}$)	0.1635	-0.1415	0.0655	0.2868	-0.0179	0.0327	0.1424	0.0277	1.0000	
ln(RATING $_{i,t-1}$)	-0.1758	0.0805	0.1777	-0.0671	0.0352	-0.1152	-0.4390	-0.0529	-0.0071	1.0000
EAST$_i$	-0.0986	0.0505	0.3237	-0.0350	0.1772	-0.0886	-0.2631	-0.1351	-0.0224	0.3691