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KNOWING WHEN TO LEAP: TRANSITIONING BETWEEN EXPLOITATIVE AND EXPLORATIVE R&D

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A common perspective is that consistent R&D investment facilitates innovation, while volatile spending implies myopic decision making. However, the benefits to exploiting extant competencies eventually erode, so firms must disrupt their R&D function and explore for new competitive advantage. We suggest that high-performing firms recognize when extant competencies decline and increase exploratory R&D to develop new competencies at the appropriate time. We find that changes in R&D expenditure away from the firm's historic trend, in either direction, are indicative of transitions between exploitative and exploratory R&D and are associated with increased firm performance. Increases in R&D expenditure above the trend are associated with an increased likelihood of highly cited patents, suggesting that firms are making the leap between R&D-based exploitation and exploration.

INTRODUCTION

When extant firm competencies are no longer valuable, the best-performing firms are able to make the leap to newer, more competitive technologies by focusing their R&D efforts on exploration. These efforts enable them to discover significant new innovations, which they are able to exploit as stability returns. This line of thinking suggests that high performing firms maintain relatively long periods of stable R&D activity, interrupted by compact, significant changes in their innovative efforts. This idea points to an important qualification to a long history of research across several disciplines.

A common view in technology and innovation management is that increasing R&D investment over time is good for firm performance. This reasoning is rooted in two bodies of literature that have developed over the past 60 years. The first may be traced to neoclassical economic theory and the economics of innovation. Scholars have argued since the 1950s that positive residuals in production function regressions, so-called 'Solow residuals,' may be attributed to R&D (Abramovitz, 1956; Solow, 1957). Beginning with Arrow (1962), traditional research in the economics of innovation maintains that society underinvests in R&D and that private firms will be particularly prone to such underinvestment. Rosenberg (1990) submits that large firms undertake R&D to defend oligopolistic positions, while small firms do so to obtain first mover advantages—both of which either maintain or enhance firm value. Cohen and Levinthal (1990) present evidence that R&D spending enables firms to increase their ability to apply knowledge to commercial ends. These studies suggest that R&D

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investment is always beneficial for the firm as well as society and that the major objective is to encourage more of it.

The second root is found in the management and accounting research. The emphasis of this body of literature is that changes in R&D expenditures are evidence of myopic investment decisions. Firms that minimize or resist opportunities to disrupt the R&D process are thought to add the most value for shareholders of the firm. Management research notes that stable investments in R&D enable firms to develop sustainable competitive advantages (Kor and Mahoney, 2005) and that productive R&D is the result of knowledge accumulation that requires steady investment over time (Dierickx and Cool, 1989). This reasoning is buttressed by accounting research suggesting that managers' incentives to smooth earnings or to meet earnings forecasts routinely lead them to manipulate research and development expenditures (Bushee, 1998), a practice that has been labeled 'earnings manipulation.' For instance, Baber, Fairfield, and Haggard (1991) maintain that managers reduce research and development expenditures when earnings will be less than analysts' forecasts. Generally, managers are thought to make ineffective decisions regarding R&D investments, focusing on short-term earnings instead of concentrating on value creation.

However, recent research shows that persistent, relatively routine changes in R&D expenditure are associated with higher firm growth (Mudambi and Swift, 2011), evidence that suggests the existence of contingencies wherein changes in R&D expenditure can be beneficial. The current paper offers a new theory that explains precisely these contingencies. We present a contextual view of the benefits to changes in R&D spending. While stability in R&D spending is often beneficial (Kor and Mahoney, 2005), there are circumstances when the firm's interests are best served by undertaking sharp changes in its R&D spending trajectory.

We know that firms go through long periods of relative stability that are interrupted by short intervals of intense change (Gilsing and Nooteboom, 2006; Miller and Friesen, 1984; Romanelli and Tushman, 1994). During these periods of stability, firms exploit their existing competencies. However, these competencies eventually wane in value. Competitors successfully imitate leading products, and breakthrough technological innovation makes earlier products obsolete (Klepper, 1996). These developments can seriously undermine the value of the firm's existing competencies, forcing it to explore for new ways to create and maintain competitive advantage. In doing so, it drastically overhauls its R&D portfolio, moving from exploitative R&D-based activities to more exploratory ones. We suggest that a compact, significant change in firm-level R&D expenditure can be an indicator that a firm is adapting to an important (and infrequent) change in the value of its competitive advantage.

This paper focuses on the impact that moving between exploration and exploitation can have on firm innovative performance. We suggest that such transitions between exploration and exploitation are quite dramatic and are observable as significant changes in firm-level R&D expenditure occurring within relatively small time windows. In light of prior research showing that R&D spending rises then falls as a new product is developed and then taken to market (DiMasi, Hansen, and Grabowski, 2003), we maintain that infrequent, seismic increases in R&D expenditure may be interpreted as evidence that a firm is moving from periods of exploitation to one of exploration. We also posit that compact, significant changes in R&D spending are beneficial to the firm, regardless of the direction of the change.

The current paper investigates empirically the relation between relatively large changes in R&D expenditure occurring within small time windows and a measure of the extent of the firm's exploratory knowledge-creation activity. We also examine the relation between this specific form of R&D expenditure volatility and multiple proxies of R&D success and firm performance, including the amount of patented knowledge, new product releases, and stock-market based firm performance. To further differentiate between the earnings manipulation and exploration/exploitation perspectives on R&D volatility, we evaluate how the firm's short-term earnings performance influences the relationship between significant, compact changes in R&D spending and firm performance. Finally, we also show that our results are robust to multiple concerns including endogeneity.

In summary, this paper makes four major contributions. First and most fundamentally, we develop a novel story that highlights the value-creating potential of disruptive changes in firm-level R&D spending and introduce a new discussion of the

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meaning of such disruptive changes. We also use an innovative estimation technique to capture accurately the essence of disruptive changes in R&D spending. Second, we show that compact, significant increases in R&D spending are associated with an increased emphasis on exploratory R&D. Third, we show that compact significant changes in R&D expenditure, whether positive or negative, benefit the firm. Fourth, we introduce new tests that evaluate the lag structure between R&D expenditure and changes in innovative output. We show that a relatively large, unexpected change in R&D spending is associated with increased patented knowledge output in the next year, or the next two years, findings that extend extant literature in the area (Hall, Griliches, and Hausman, 1986).

THEORY AND HYPOTHESES

Firms engage in research and development to create competitive advantages and increase firm value (Hall, Jaffe, and Trajtenberg, 2005; Jaffe, 1986; Pakes, 1985). Yet, managing this R&D process is challenging as it involves technological uncertainty and can be opaque to nonspecialists (Mudambi and Swift, 2009). In addition, breakthroughs are difficult to predict or forecast, while cash expenditures are easy to observe. Thus it may be difficult for firms to change their R&D expenditure profiles over time because it is difficult to gather reliable information with which to judge the prospects of their R&D portfolios.

Organizations benefit from both the 'exploration of new possibilities' as well as from the 'exploitation of old certainties' (March, 1991: 71). A reliance on either process to the exclusion of the other is likely to lead to suboptimal outcomes, so that maintaining the appropriate balance between exploration and exploitation is critical for an organization's success and even for its very survival. Firms in competitive markets generate economic rents by exploiting their current sources of competitive advantage. However, these current advantages are continuously eroded through imitation by rivals and through technological advances, so that eventually all firms must explore for new sources of competitive advantage if they are to survive and thrive (Leonard-Barton, 1992; Levinthal and March, 1993).

Exploitation processes aim to achieve refinement, efficiency, production, and execution, objectives that are best achieved in stable and predictable environments (Benner and Tushman, 2003). On the other hand, exploration processes focus on risk taking, search, experimentation, discovery, and radical innovation, activities that are associated with rapid change (March, 1991). Successful exploitation is associated with maximizing the current value of the firm's existing resource endowment, while successful exploration is the basis of the development of new competencies (Cantwell and Mudambi, 2005). Firms that exhibit sustained competitive advantage must be able to do two things. First, they must defend their exploitation of current competitive advantages over long periods of time (Porter, 1985). Second, they must also recognize the environmental cues that indicate the costs of defense are beginning to exceed benefits and implement disruptive exploration processes in order to develop new competencies (Cockburn, Henderson, and Stern, 2003).

However, the skills required to undertake exploration and exploitation are orthogonal (March, 1991, 1996, 2006). Thus, it is costly and difficult for the firm to undertake transitions between these two modes of R&D-based activity. We posit that only the most successful firms will respond effectively to both the long periods of stability as well as the short periods of disruptive change. Effective R&D management should result in expenditures that reflect these strategic realities: periods of relative stability interrupted by periods of extreme change. These arguments imply a specific characterization of the R&D spending profile of successful firms. Consistent with much of the extant research literature, they must maintain a stable profile of R&D expenditure over the long periods of time during which they exploit extant competencies (Dierickx and Cool, 1989; Kor and Mahoney, 2005). However, they also must recognize those infrequent, but critical, points in time when either imitation by rivals or technological advance erodes the value of these competencies (Klepper, 1996). At these points, they must implement major shifts in their R&D expenditures and create new knowledge (Mudambi, 2008). In short, their R&D spending profile is characterized by long periods along a stable trend, interrupted by short time intervals that exhibit dramatic change.

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R&D expenditure manipulation

Compelling theoretical arguments suggest that fluctuations in R&D can hurt firm performance. Research workers have highly specialized skills that make them particularly well suited to a unique research project (Wang, He, and Mahoney, 2009). If such R&D team members are fired based upon the firm's short-term financial condition, they cannot easily be rehired, resulting in employee turnover that can disrupt the R&D function (Grabowski, 1968; Hambrick, MacMillan, and Barbosa, 1983).

Further, prior research suggests that there are many circumstances in which firms tend to adjust their R&D expenditures to meet earnings forecasts, disrupting the research process and destroying firm value (Baber *et al*., 1991; Bushee, 1998; Dechow and Sloan, 1991). The earnings manipulation hypothesis is implicitly based on the idea that consistently investing in R&D over time maximizes progress towards valuable innovations and enhances firm value. In other words, if R&D expenditure volatility emanates from decisions undertaken to meet short-term earnings targets, (i.e., earnings manipulation activity), it can impede the real work underway in the R&D lab. This literature suggests that, if a firm reduces the funding to an R&D project at a time when the project is nearing a major accomplishment, the opportunity cost to the firm can be enormous.

Compact, significant increases in R&D expenditure and exploratory R&D

However, earnings management is not the only source of volatility in R&D expenditure. We maintain that the movement between exploitation and exploration processes induces substantial disruption in the firm's R&D function and hence in the level of R&D spending. In our developed framework, the level of firm-level R&D spending is influenced by the type of R&D work underway within the firm at any point in time.

Gagnon and Lexchin (2008) show that exploration is associated with a large majority of pharmaceutical R&D expenditures. DiMasi *et al*. (2003) provide data suggesting that in the pharmaceutical industry, early-stage product development activities require higher levels of R&D expenditure than late-stage work, suggesting that exploratory R&D is more costly than exploitative.[1] Other research shows that exploratory R&D-based activities are more costly than exploitative ones in the automotive industry (Clark, Chew, and Fujimoto, 1987; Clark and Fujimoto, 1991; Dyer, 1996; Harryson, Dudkowski, and Stern, 2008). Exploratory product development represents 'the bulk of R&D expenditures' (Clark *et al*., 1987: 730) in the product development cycle of an automobile model.

Exploratory R&D involves nonlocal search that requires synthesizing diverse bodies of knowledge and moves the firm on to a new technology trajectory (Argyres, 1996). The returns to this form of R&D have been characterized as 'uncertain, distant, and often negative' (March, 1991: 85). Hence we maintain that firms undertake such expensive and risky investments only when they have no alternative. There is evidence that 'technology exhaustion' in their current portfolio of R&D activities (Ahuja and Katila, 2004) drives firms to explore new fields. This evidence is consistent with our idea of transition from exploitative to exploratory R&D.

The empirical evidence suggesting that exploratory R&D is more expensive than exploitative R&D, (Clark and Fujimoto, 1991; Clark *et al*., 1987; DiMasi *et al*., 2003; Dyer, 1996; Gagnon and Lexchin, 2008; Harryson *et al*., 2008) leads to the following implication: a move from R&D-based exploitation to exploration should involve a dramatic increase in R&D spending. Similarly, compact, significant decreases in R&D spending may be associated with a transition from R&D-based exploration to exploitation.

Extant research defines exploitation activities as those in which the firm leverages its existing knowledge base, while exploration involves

[1] Clinical trials constitute as much as 70 percent of the total costs of drug development (DiMasi *et al*., 2003). The bulk of these expenses may be considered explorative R&D because they can be traced to the trials of what the FDA calls 'new molecular entities' (NMEs) (Dunlap-Hinkler *et al*., 2010). The preclinical phase takes an average of 18 months (Giovannetti and Morrisson, 2000; PhRMA, 2011) while Phases I, II, and III take an average of six years (Califf *et al*., 2012) and have a success rate of less than two percent (DiMasi, *et al*., 2010). In contrast, clinical trials for subsequent modifications of NMEs, what the FDA calls 'efficacy supplements' (ESs) may be considered exploitative R&D; they are much cheaper since they may skip many of these requirements, can use prior results from the clinical trials of the NME on which they are based, and take an average of less than 10 months (FDA, 1998).

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the search for new knowledge in domains that are relatively distant from the firm's core base of knowledge (Baum, Li, and Usher, 2000; Benner and Tushman, 2003; Rosenkopf and Nerkar, 2001). Firms undertaking exploitative R&D will conduct knowledge-creation activities within a narrow range of technological areas; i.e., their R&D activities will display narrow technological scope. In contrast, firms pursuing exploratory R&D will create knowledge in a wider range, so that their R&D displays broad technological scope (Sorenson, *et al*., 2006). If a compact, significant increase in R&D spending is evidence that a firm is moving its emphasis from exploitation to exploration, then such changes in R&D expenditure will be associated with significant widening of the technological scope of the firm's knowledge-creation activities. Thus

Hypothesis 1: Significant, compact increases in R&D spending are positively associated with increased exploratory R&D.

The early-stage costs incurred in exploratory R&D are significant; explicit estimates have been computed in a number of industries, including pharmaceuticals, biotechnology, and automobiles (DiMasi and Grabowski, 2007; Gagnon and Lexchin, 2008; Grabowski and Vernon, 1990; Harryson *et al*., 2008). The technology management literature has often characterized successful exploratory R&D processes as leading to breakthrough innovation (Dosi, 1982; Sheremata, 2004). Such innovation has been operationalized in several different ways. One of the most widely used is the creation of highly cited patents (Ahuja and Lampert, 2001; Almeida and Kogut, 1999). This operationalization is justified by the substantial evidence that links highly cited patents with a number of other measures of successful exploratory R&D including science-based new product introductions (Ahuja and Katila, 2001; Dunlap-Hinkler *et al*., 2010). Hence, following our reasoning that significant, compact increases in R&D are markers of a transition to exploratory R&D processes, we state the following hypothesis:

Hypothesis 2: Significant, compact increases in R&D spending are positively associated with an increased probability of creating a highly cited patent.

The importance of the timing of compact, significant changes in R&D expenditure

The second important dimension of R&D change is its timing. Managers must perceive the need to change the firm's emphasis (either from exploitative to exploratory R&D or the reverse) and act on this perception. However, they also must get the timing right. If the firm moves from exploitative to exploratory R&D while its existing competencies are still valuable, it will incur high opportunity costs. If the firm transits from exploratory R&D to exploitative before it has created a new form of competitive advantage, it will fail to reap a significant return on its R&D investment.

We posit that compact, significant changes in R&D expenditure can also be due to management's interpretation of the cues emanating from the external environment and that the managers of the best firms know when to make the leap. Over time, the value of the firm's extant innovations begins to wane as market competitors make inroads against the firm's innovation. The benefits to exploitation processes (e.g., further refinements) decrease while the benefits to exploration processes (e.g., search and experimentation) increase. Eventually, the benefits to exploration (i.e., discovering a new commercially valuable innovation that can restore or enhance the firm's competitive position) exceed the benefits to continuing to exploit the old competency. Once this point occurs, it pays for the firm to move from exploitation mode to exploration mode.

Infrequent but drastic changes in R&D expenditures within small time windows are consistent with the firm's managers recognizing the need to change the firm's R&D emphasis. Firms that are able to maintain high performance can consistently pick the most appropriate circumstances for exploration. This firm capability ensures that such disruptive shifts in R&D expenditure lead to superior performance in terms of R&D-related outputs.

If it is timed correctly, a dramatic shift in R&D expenditure *in either direction* can have positive payoffs. Increased exploratory R&D can lead to highly cited, breakthrough patents in new areas of innovation. Increased exploitative R&D can lead to a series of valuable patents in a concentrated area of innovation. This logic leads to the following hypothesis:

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Hypothesis 3: Significant, compact changes in R&D spending are positively related to firm R&D-related outputs.

Firms that are more effective at moving between exploration and exploitation will tend to outperform those that are less effective, because they 'are not only efficient, but can also cope with unpredictability' (Anderson and Tushman, 2001: 682). Indeed, maintaining an appropriate balance between exploration and exploitation processes increases the firm's chances of survival and prosperity (March, 1991). These firms are able to generate sustained competitive advantage; they defend current sources of advantage through exploitative R&D but also renew their advantage by developing new competencies through explorative R&D. This reasoning leads to the following related hypothesis:

Hypothesis 4: Significant, compact changes in R&D spending are positively related to firm performance.

R&D volatility and relative earnings underperformance

The business press routinely observes that managers are under great pressure to meet current earnings targets (Hansen and Hill, 1991). Prior research has documented two circumstances under which firms change their level of R&D expenditure in a manner consistent with this view. R&D spending is more likely to be reduced when the CEO approaches retirement (Dechow and Sloan, 1991) or when the firm is likely to miss an earnings objective (Baber *et al*., 1991). Firms with high operating cash flow volatility not only delay research and development investment during periods of weak operating performance, but also permanently forego R&D investment (Minton and Schrand, 1999).

Yet others have maintained that high performing firms do not use R&D in order to manipulate earnings in the short run. Firms cannot regain lost R&D outputs from periods of decreased R&D investment by increasing spending during periods of strong operating performance—missed opportunities will likely disappear as they are exploited by competing firms or bypassed by competing technologies (Lilien and Yoon, 1990). R&D expenditure volatility that emanates from entrenched executives using R&D spending as a buffer to improve short-term earnings should enable the firm to meet short-term earnings targets. However, volatility that stems from such activity can damage the long-term viability of the firm.

The behavioral theory of the firm (Cyert and March, 1963) suggests that firms manage their performance relative to aspirations and measure risk as the likelihood of missing performance aspirations. Subsequent research has supported this assertion. Executive decision makers (Mao, 1970; March and Shapira, 1987) and financial analysts (Baird and Thomas, 1990) describe risk as the frequency and magnitude of negative outcomes. When considering firm risk, measuring the extent to which the firm misses its earnings objective has theoretical and practical appeal (Menezes, Geiss, and Tressler, 1980; Miller and Leiblein, 1996).

This discussion leads to our fifth hypothesis. Presumably, high-performing firms do not use R&D expenditures to manipulate short-term earnings (Dierickx and Cool, 1989; Minton and Schrand, 1999). While such a strategy successfully links significant, compact changes in R&D expenditure to *sustained* superior performance, it comes at a cost in terms of short-term performance. Pursuing opportunities when they arise, regardless of the current financial position of the firm, has, on average, a negative impact on short-term earnings. Hence:

Hypothesis 5: The relationship between significant, compact changes in R&D spending and sustained firm performance is stronger among firms that generate short-term earnings that are more frequently and substantially below their industry peer groups.

DATA AND VARIABLES

Our hypotheses imply three testable models. In the first model (corresponding to Hypothesis 1), the dependent variable is the technological scope of the firm's knowledge creation, while in the second model (Hypotheses 2 and 3), the dependent variable is firm-level innovative performance. In the third model (Hypotheses 4 and 5), the dependent variable is a market-based measure of overall firm performance. The next steps are to develop econometric specifications corresponding to each model, to identify appropriate variables, and to construct datasets to run empirical tests.

The data

Our sample frame is generated from the Compustat Annual North America databases (Standard & Poors, 2009), which provide accounting and market information on all publicly traded firms in the U.S. In order to test our hypotheses, we gather financial, economic, and R&D-related data on a sample of publicly traded U.S. manufacturing firms.

We constructed several specific datasets to test our hypotheses. We draw financial and data from Compustat. Following Hall *et al*. (2005), all manufacturing firms (NAICS codes 31 through 3,399) are selected. This dataset covers the years 1997–2006. Each observation represents one firm-year. After removing observations with missing values, the dataset contains 11,140 firm-year observations.

We constructed additional datasets to test Hypotheses 1, 2, and 3. These hypotheses relate to firm-level knowledge creation and innovation. Based on the knowledge creation and innovation literature, we measure R&D-related output in four ways. First, we measure the technological scope of the firm's knowledge-creation activities by observing the dispersion of the firm's citation-weighted patents across technological classes. Second, we measure the firm's effectiveness at performing exploratory R&D by using the odds that the firm creates a highly cited patent. Third, we use firm patents and patent citations as a proxy of firm knowledge creation (Cockburn and Henderson, 1998; Henderson and Cockburn, 1994; Jaffe, 1986; Pakes, 1985; Shan, Walker, and Kogut, 1994; Zucker, Darby, and Armstrong, 2002). However, patents do not capture all forms of firm innovation (Helfat, 1994; Roberts and Amit, 2003). Therefore, new product introductions are used as another measure of innovation output (Barnett and Freeman, 2001; Coombs, Narandren, and Richards, 1996; Roberts and Amit, 2003).

Patents and patent citations

All patent and patent citation data are taken from the most comprehensive available data source, namely the NBER U.S. Patent Citations Data File (Hall, Jaffe, and Trajtenberg, 2001), which has recently been updated to include patents and citations through 2006. This file contains detailed information on more than 3 million U.S. patents from 1963 to 2006 and all citations made to these patents from 1975 to 2006. To the extent possible, these patents have been matched to U.S. publicly traded firms listed in the Compustat databases.

New product releases

Several researchers have used the business press as a source for new product releases (Barnett and Freeman, 2001; Coombs *et al*., 1996; Roberts and Amit, 2003). The Lexis-Nexis Academic database (Lexis-Nexis, 2007) is used to search the PR Newswire and Business Wire press release distribution services for new product press releases that were issued by the 3,089 firms in our sample during the 2002–2006 study period. We find 6,479 new product releases from the firms in our sample during that time period.

Dependent variables

Firm knowledge creation

The number of patents granted to a firm and the number of citations a firm's patents have received from subsequent patents are commonly used to measure firm knowledge creation (Cockburn and Henderson, 1998; Henderson and Cockburn, 1994; Jaffe, 1986; Pakes, 1985; Shan *et al*., 1994; Zucker *et al*., 2002;). A highly cited patent is judged to be more 'valuable' than a patent that has received relatively few citations from other patents over time (Hall *et al*., 2005).

Hall *et al*. (2001) observe that the number of patents granted has increased sharply since 1983 and that each patent is receiving more citations over time. In addition, the number of patents granted and the number of citations received per patent varies by technological field (Hall *et al*., 2001). Finally, patent citations are truncated at the date of observation. *Ceteris paribus*, a patent that was granted last year has received fewer citations than a patent that was granted five years ago, because the former patent has been available to cite for less time. As a result, care must be given when comparing patents and patent citations from different industries and different years. Due to these systematic differences in patent grant rates

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and patent citation activity over time and among industries, we adopt Hall *et al*.'s (2001) 'fixed-effects' approach. Each patent's citation count is divided by the average number of citations received for all patents granted in the same industry, during the same year. Firm knowledge creation is thus measured as follows:

$$\text{Firm Knowledge Creation} = \text{patents}\, f, t * \frac{\text{citations received}\, f, t}{\left[\frac{\text{citations received } i,t}{\text{patents granted } i,t}\right]} \quad (1)$$

where f = firm, i = industry, and t = year.

Technological scope knowledge creation

The United States Patents and Trademark Office (USPTO) has categorized all patents into roughly 470 broad technological categories (i.e.: a class) and 150,000 specific technological subclasses (USPTO, 2007). These categories are used to measure the technological scope of the firm's patenting activity. The technological scope of the firm's patenting activity is estimated using a two-step process.

First, the amount of knowledge that the firm has created in each technological subclass is estimated using the same methodology described above under 'Firm Knowledge Creation.'

Second, the dispersion of this firm-level knowledge creation across technological subclasses is measured using an entropy index (Theil, 1967), as follows:

$$\text{Scope of knowledge creation} = \sum_{n=1}^{\#\text{ of technological subclasses}} [PK_n * \ln(1 \div PK_n)] \quad (2)$$

where PK_n = percentage of firm knowledge granted in USPTO technological subclass n.

Highly cited patents

In order to determine whether a patent is highly cited, one must calculate citations per patent. As noted above, number of citations received per patent varies by industry and, *ceteris paribus*, older patents have more citations than newer patents (Hall *et al*., 2001). Therefore, citations per patent are estimated by using a modified version of Hall *et al.'s* (2001) 'fixed-effects' approach. Citations per patent are divided by the average number of citations per patent in the same industry, in the same year.

$$\text{Citations per patent} = \frac{\left[\frac{\text{citations received } f,t}{\text{patents granted } f,t}\right]}{\left[\frac{\text{citations received } i,t}{\text{patents granted } i,t}\right]} \quad (3)$$

where f = firm, i = industry, and t = year.

The distribution of citations per patent is severely right skewed. Therefore, patents in the highest percentiles have significantly higher citations per patent than the rest of the sample. An arbitrary cutoff of the 10th percentile was selected to distinguish 'highly cited' patents from the rest of the sample.

In tests that evaluate whether a compact, significant increase in R&D spending is related to the probability of creating a highly cited patent, we use the natural log of the odds (logit) of the firm creating a patent that is in the top 10 percent of most cited patents in the years immediately following this shift in R&D spending. This procedure requires that we develop an indicator-dependent variable. If the firm generates a highly cited patent in the year that the firm's largest increase in R&D spending occurs, or the two years following, the dependent variable is set to 1. Otherwise, the dependent variable is set to 0. This procedure enables us to evaluate whether the magnitude of the firm's largest increase in R&D spending is related to increased odds of creating a highly cited patent in the proximate future.

New product introductions

The Lexis-Nexis Academic Databases (Lexis-Nexis, 2007) hold all press releases circulated by Business Wire and PR Newswire. We searched those wire services for each firm within our sample that reported financial results in Compustat between 1997 and 2006. A simple count of new product press releases was made for each firm, from all press releases issued from 2002 to 2006. If more than one press release was issued for the same product, only the first press release was counted.

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Firm performance

Firm performance is measured using a well-known proxy for Tobin's q (Chung and Pruitt, 1994). Tobin's q is defined as the ratio of the market value of a firm to the replacement cost of its assets. Firms with q greater than one are creating economic value, since such firms can be sold for more than it costs to obtain their assets. In our estimate of q, we use the book value of assets as an estimate of replacement costs of assets (Chung and Pruitt, 1994).

Independent variables

Compact, significant changes in R&D expenditure

We have maintained that compact, significant changes in R&D expenditure can be an observable marker for the proactive approach to R&D management required under conditions of punctuated equilibrium. We measured it over the 10-year study period as maximum of the absolute values for all residuals for the firm from a Generalized Autoregressive Conditional Heteroskedastic (GARCH) time trend of R&D spending that the firm exhibits over the 10-year study period. This measures unexpected changes in R&D spending net of R&D expenditure growth and also identifies the most extreme change in R&D spending relative to all of the changes that the firm exhibits during the study period.

The calculation is performed using a three-step process. First, we estimate the R&D expenditure trend over time using a GARCH model. This GARCH trend enables us to estimate the frequency of and extent to which the firm's R&D spending diverges from a forecast that one would have predicted reasonably based on the firm's historical R&D expenditure trend (Anderson and Tushman, 2001; Folta and O'Brien, 2004; Oriani and Sobrero, 2008). Since we have a relatively short time series of firm-level data, we include the first-order autoregressive term of the dependent variable in order to improve the accuracy of our model (Anderson and Tushman, 2001; Folta and O'Brien, 2004; Oriani and Sobrero, 2008).

Estimating this GARCH equation gives us the trend value of R&D expenditure. The residuals around this trend line, e_i, are our measure of the change in R&D expenditure. A firm with very small residuals is interpreted as a firm with a very smooth R&D expenditure profile.

Second, we normalize these residuals, recognizing that in order to compare one with another, it is necessary to incorporate the variance of the stochastic process that generated them. Therefore, we generate studentized residuals, which are defined as:

$$e_{it}\,(\text{stud}) = \frac{e_{it}}{\left[s_i\sqrt{(1-h_{it})}\right]} \tag{4}$$

where $s_i = \sqrt{\text{variance}\,(e_{it})}$, $1997 < t < 2006$[2] $h_{it} = \text{leverage}\ (e_{it})$. Carriage return third, when testing Hypotheses 1 and 2, we find the maximum of all residuals for the firm, i.e., $e_i(\max) = \text{Max}_t[e_{it}(\text{stud})]$, $1997 < t < 2006$. When testing Hypotheses 3 through 5, we find the maximum of the absolute values for all residuals for the firm for each firm, i.e., $e_i(\max) = \text{Max}_t[\text{abs}(e_{it}(\text{stud}))]$, $1997 < t < 2006$.[2]

We believe this approach picks up the extent to which the firm makes a dramatic, compact change in R&D expenditure. Firms that do not make substantial changes over the study period will have a relatively small maximum studentized residual. Firms that make one or two substantial changes in R&D expenditure will have a larger maximum studentized residual. Note that firms that follow a predictable cycle of changes in R&D expenditure will have a smaller maximum studentized residual. This outcome occurs because a studentized residual is calculated by dividing a forecast residual by the standard deviation of all residuals from the firm-level time series forecast. Thus, a firm with several large residuals will generate a large standard deviation across the residuals, which will result in a set of relatively small studentized residuals. Only firms with a set of relatively small residuals and few large residuals will generate a large studentized residual.

In order to determine whether the changes we predict occur after the firm's significant, compact change in R&D expenditure, we develop a set of indicator variables. When testing Hypothesis 1, we create an indicator-independent variable based on when we observe the largest change in R&D spending. The indicator variable is set to the value as calculated in the three-step process shown immediately above in the year that

[2] For specifications using new product releases as the dependent variable, note that *t* runs from 1999 to 2006.

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the shift occurs and the two years following. The measure of significant, compact changes in R&D spending is set to zero in all other years. This procedure enables us to determine whether the technological scope of the firm's knowledge creation increases after the firm's largest increase in R&D spending over the study period.

We use a similar approach to developing the independent variable when testing Hypothesis 3. However, we use the absolute value of the firm's significant, compact changes in R&D spending in the year that the most significant shift occurs and the two years following. This enables us to evaluate whether compact significant changes in R&D spending, regardless of the direction, are associated with increased innovative output.

When testing Hypotheses 4 and 5, we use Tobin's q as the dependent variable and develop a constructed variable based on Tobin's q. This procedure is done in order to avoid linking Tobin's q to future changes in R&D spending, rather than proximate past ones. In the years prior to the firm's most significant shift in R&D spending, the measure of significant, compact changes in R&D spending is set to zero. In the year that the shift occurs and all years following, the constructed variable is set to the value as calculated in the three-step process shown above.

Firm earnings underperformance relative to industry peers

As stated in Hypothesis 5, we expect that significant, compact changes in R&D spending will have a greater effect on firm performance in firms that more frequently and substantially underperform their industry peers. The notion of risk in the behavioral theory of the firm (Cyert and March, 1963) has been operationalized as a lower partial moment (LPM) of the firm's earnings underperformance relative to target (Miller and Leiblein, 1996; Miller and Reuer, 1996). We posit that the firm's earnings benchmark is the average return on assets of the industry within which the firm competes from the previous year (Miller and Leiblein, 1996; Miller and Reuer, 1996). LPM measures have some appealing theoretical properties. It has been shown that downside risk reduces an individual's utility regardless of the individual's risk preferences (Menezes *et al*., 1980). The general form of the LPM measure is:

$$RLPM = \sqrt[n]{(1/m)\sum_{1}^{m}(x)} \quad (5)$$

where m = number of time periods used in the measure, n is an arbitrary integer greater than or equal to 2, and x = target − actual. If target < actual, then x is set to 0.

Since the firm's most recent earnings performance is likely to bear the most heavily on the firm's current investment decisions, we set m equal to 2 and n equal to 2.

CONTROL VARIABLES

There is a broad literature providing empirical support for many different factors that affect firm performance. In addition to controlling for firm-level differences using firm-level fixed effects in the regression analyses that follow, we seek to control for intertemporal differences using time-varying control variables before testing our research hypotheses.

Tobin's q is generally viewed to be an indication of the firm's future growth prospects (Lang, Ofek, and Stulz, 1996). Firm sales growth over the previous year is included to control for this influence. Earnings per share (net income divided by shares outstanding) is included to capture the effect of firm profitability on Tobin's q (Erickson and Whited, 2000), and the level of firm sales is included to control for firm size (Chesher, 1979; Montgomery and Wernerfelt, 1988). R&D intensity is included as a control variable, since several researchers have shown a relationship between R&D intensity and firm performance (Hall *et al*., 2005). Firm value has been shown to decrease over corporate diversification (Berger and Ofek, 1995; Campa and Kedia, 2002). An entropy index (Theil 1967) is used to measure firm diversification (Hitt, Hoskisson, and Kim, 1997), which is calculated as follows:

$$\text{Firm diversification} = \sum_{n=1}^{\#\text{ of divisions}} [P_n * \ln(1 \div P_n)] \quad (6)$$

where P_n = percentage of firm revenues derived by division n. Multiple divisions that are reported in

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the same six-digit NAICS code are treated as one division.

Lang *et al*. (1996) find that firm leverage effects Tobin's q. The firm's debt ratio (long-term debt divided by total assets) is included to control for the influence of leverage.

When using new product releases as our dependent variable, we are unable to include firm-level fixed effects. In this specification, we include additional control variables to capture important interfirm differences. Highly concentrated industries are viewed as less competitive; firms in such industries enjoy high entry barriers and may appropriate economic rents (McGahan and Porter, 1997). Therefore, we include the U.S. Economic Census' measure of industry concentration (market share of the twenty largest firms in each four-digit NAICS industry) (U.S. Census Bureau, 2002). In practice, many firms set R&D spending targets as a percentage of expected firm sales (Scherer, 2001). We include a measure of sales volatility, which is calculated using the same methodology as compact, significant changes in R&D expenditure, in order to control for the volatility in firm sales over time.

EMPIRICAL ANALYSIS

Table 1 presents the summary statistics of the sample data. The measure of compact, significant changes in R&D spending is the largest change in firm-level R&D spending over the 10-year study period. The measures of firm performance, firm earnings underperformance relative to industry peers, firm size, firm debt, and firm R&D intensity are highly skewed and are therefore log-transformed. Note that new product releases are the average value for each firm-year in the year of the largest change in firm-level R&D spending and two years following the change. The positive correlation between the technological scope of firm knowledge creation (over the 470 USPTO technology classes) and firm knowledge creation (the citation-based measure defined in Equation 1) suggests that firms undertaking exploratory R&D create more patented knowledge. Firm size is positively correlated to the technological scope of firm knowledge creation and industrial diversification, suggesting that as the firm grows, it undertakes more industrial diversification (Rumelt, 1974). It is noteworthy that firm R&D intensity is negatively correlated to firm size, suggesting that larger firms may enjoy the benefits of scale in R&D.

Primary tests

Fixed-effects multiple regression analysis is used to test each hypothesis except the alternative test using new product releases as the dependent variable measuring firm innovative output.[3] For all equations using Tobin's q or changes in the technological scope of firm's knowledge creation as the dependent variables, heteroskedasticity-corrected estimates are presented using feasible generalized least squares (FGLS). For all equations using patents or new product releases as the dependent variables, negative binomial regression is used. While many similar studies have used a Poisson regression (Azoulay, Ding, and Stuart, 2009; Azoulay, Graff Zivin, and Wang, 2010), the mean value of the dependent variable indicates a negative binomial regression is more appropriate in our case.

When testing Hypotheses 1 and 2, fewer observations are used to estimate the regression equations compared to the test of Hypothesis 3. In order to test Hypothesis 1, we calculate the technological dispersion of firm knowledge creation. In order to test Hypothesis 2, we calculate the number of citations to the firm's patents in each year. If a firm has no patents in a given year, the value of the dependent variables for the tests of Hypotheses 1 and 2 are missing and are dropped from the test.[4] In contrast, in order to test Hypothesis 3, we calculate the firm's total patented knowledge creation in each year. If a firm has no patents in a given year, the value of the dependent variable in Hypothesis 3 is set to 0, and the data record is included in the test. Some firms reported the financial information required to measure the

[3] Since our new product dataset includes only five years of new product releases, a time series approach to this specification is not appropriate. When using new product releases as the dependent variable, we regress product releases in the year the largest change in R&D spending is observed and the two years following that change, on the average value of each of the control variables at the firm level over the five-year study period.

[4] This approach could be criticized as selecting on the dependent variable. We conducted a sample selection model (Heckman, 1979), which allows for missing values for the dependent variable. We used capital intensity to estimate the firm's propensity to patent (Acs and Audretsch, 1989), testing the errors for normality to ensure the appropriateness of the probit model in the first stage (Wilde, 2008). These results are consistent with the main results of this paper.

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Table 1. Summary statistics

Simple statistics			Pearson correlation coefficients											
Variable	Mean	Std. dev.	1	2	3	4	5	6	7	8	9	10	11	12
1. Firm performance	0.24	1.01												
2. Firm knowledge creation	20,945.00	171,653.00	−0.04											
3. New product releases	0.37	1.93	0.02	0.11										
4. Technological scope of firm knowledge creation	0.56	0.67	−0.10	0.26	0.06									
5. Citations per patent	1.05	1.31	0.07	0.00	0.03	0.01								
6. Compact, significant changes in R&D expenditure	0.91	7.60	0.02	0.03	−0.06	−0.02	0.00							
7. Firm earnings underperformance relative to industry	0.04	0.07	0.12	0.01	0.05	0.00	0.03	−0.04						
8. Firm size	5.56	2.54	−0.25	0.21	0.13	0.50	−0.05	−0.05	0.09					
9. Firm debt	0.13	0.15	−0.09	−0.01	−0.04	0.06	−0.04	0.02	−0.16	0.20				
10. Firm profitability	−66.57	6,392.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	−0.01	−0.01			
11. Firm R&D intensity	0.27	0.67	0.26	−0.03	−0.05	−0.16	0.02	0.04	−0.16	−0.52	−0.10	0.00		
12. Firm industrial diversification	0.25	0.42	−0.20	0.13	0.00	0.32	−0.07	0.00	−0.06	0.49	0.19	0.01	−0.20	
13. Firm growth	8.89	527.54	−0.01	0.00	−0.01	0.01	0.00	0.00	−0.01	0.01	0.00	0.00	0.00	0.02

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Table 2. Significant, compact increases in R&D expenditure and innovation

	Dependent variables			
	Technological scope of knowledge creation		Logit of highly cited patent	
	(1)	(2)	(3)	(4)
Intercept	−0.13***	−0.13***	−3.31***	−3.30***
	−10.04	*−10.39*	*279.58*	*280.74*
Compact, significant changes in R&D expenditure		0.01***		0.02**
		4.59		*5.97*
Firm size	0.13***	0.13***	−0.14***	−0.14***
	50.90	*51.04*	*14.06*	*15.13*
Firm profitability	0.00*	0.00*	0.00	0.00
	1.87	*1.87*	*0.23*	*0.24*
Firm debt	−0.12***	−0.13***	0.57	0.57
	−4.20	*−4.36*	*1.80*	*1.84*
Firm R&D intensity	0.15***	0.14***	0.04	0.02
	18.28	*18.14*	*0.15*	*0.05*
Firm industrial diversification	0.13***	0.13***	−0.34	−0.35
	8.64	*8.70*	*2.07*	*2.26*
R-square	0.2496	0.2552		
F-statistic	789.77***	678.24***		
Incremental F test		14.70***		
Log-likelihood			40.83	45.79
Log-likelihood ratio				9.92***
	n = 11,181	n = 11,181	n = 11,181	n = 11,181

We test whether compact, significant increases in R&D expenditure impacts firm innovation. First, we test whether the technological scope of the firm's knowledge creation is related to the largest increase in the firm's R&D spending during the study period. Next, we test whether a compact, significant increase in R&D spending is associated with the odds of creating a highly cited patent. In columns one and two, t-statistics are shown in *italics* under parameter estimates. Wald chi-squares are shown in columns three and four.
Firm-level fixed effects are included in all specifications.
*significant at 10%; **significant at 5%; ***significant at 1%.

control variables, but not all of the data required to calculate Tobin's q. Therefore, fewer observations are included when testing Hypotheses 4 and 5.

Hypothesis 1 predicts that there is a positive relationship between compact, significant increases in R&D expenditure and the firm's technological scope of knowledge creation. We regress the technological scope of the firm's knowledge creation on an indicator variable that is set to the largest change in R&D spending in the year of the firm's most significant spending shift and the two years following the shift and is set to 0 in all other years.

The results of the analysis using the technological scope of the firm's knowledge creation as the dependent variable are presented in Table 2 columns one and two. The regression analysis using only the controls is shown in column one, and the estimate of the specification including the indicator independent variable is shown in column two. The incremental F-test indicates that the explanatory power of the specification including the intervention variable (column two) is statistically significantly greater than the controls-only specification (column one). The parameter estimate on the intervention variable is positive and statistically significant. Hypothesis 1 is supported.

Hypothesis 2 predicts that there is a positive relationship between compact, significant increases in R&D expenditure and the odds that the firm creates a highly cited patent. The results of the logit analysis where the dependent variable takes the value of 1 when the firm creates a highly cited patent in the year the largest increase in R&D occurred, and the two years following are presented in Table 3 columns three and four.

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Table 3. Significant, compact changes in R&D expenditure and firm innovation

	Dependent variables			
	Firm knowledge creation		New product releases	
	(1)	(2)	(3)	(4)
Intercept	−2.65***	−2.65***	−5.03***	4.64***
	1399.16	*1404.42*	*211.91*	*178.23*
Compact, significant changes in R&D expenditure		0.07***		0.40***
		10.03		*11.89*
Firm size	1.38***	*1.38****	0.48***	*0.29****
	21892.6	*21133.6*	*70.34*	*14.38*
Firm debt	1.46***	*1.46****	−6.10***	*−4.36****
	105.69	*105.25*	*35.74*	*17.68*
Firm profitability	0.00***	*0.00****	0.00	*0.00*
	0.40	*0.42*	*0.04*	*0.06*
Firm R&D intensity	2.22***	2.21***	0.55***	−0.02
	796.07	*786.09*	*6/67*	*0.01*
Sales volatility			−0.0002	*−0.0003***
			3.33	*5.82*
Log-likelihood	−66714.25	−66708.95	−538.48	−506.01
Log-likelihood ratio		110.35***		64.94***
	n = 20,157	n = 20,157	n = 3,089	n = 3,089

We test whether the timing of compact, significant changes in R&D spending impacts the firm's innovative output. First, we test whether a compact, significant change in R&D expenditure is associated with the firm's knowledge creation. Next, we test whether a compact, significant changes in R&D expenditure results in higher levels of new product releases. Wald chi-squares are shown in *italics* under parameter estimates.
Firm-level fixed effects are included in columns 1 and 2.
*significant at 10%; **significant at 5%; ***significant at 1%.

The regression analysis using only the controls is shown in column three, and the estimate of the specification including the measure of the largest compact, significant increase in R&D spending is shown in column four. The log likelihood ratio indicates that the explanatory power of the specification including the independent variable (column four) is statistically significantly greater than the controls-only specification (column three). The parameter estimate on measure of a compact, significant change in R&D spending is positive and statistically significant. Hypothesis 2 is supported.

The results of the analysis estimating the relationship between the absolute value of the largest change in R&D spending and firm knowledge creation is presented in Table 3 columns one and two. The estimate of the base specification is shown in column one, and the estimate of the specification including compact, significant changes in R&D expenditure is shown in column two. The log likelihood ratio indicates that the explanatory power of the specification including compact, significant changes in R&D expenditure (column two) is statistically significantly greater than the controls-only specification (column one). The parameter estimate on compact, significant changes in R&D expenditure is positive and statistically significant. Using firm knowledge creation as the dependent variable, we find evidence that punctuated changes in R&D expenditure are positively related to R&D-related outcomes, which corroborates Hypothesis 3.

Next, we use firm new product releases as a measure of R&D-related output. We estimate the relationship between the absolute value of the largest most significant change in R&D spending and the firm's new product releases in the three years following the change. [5] The results of this analysis are shown in Table 2 columns three and four. The results of the regression analysis using the base specification only is shown in column three, and the specification including

[5] Note that we use R&D spending from 1999 to 2006, so that we can use a historical trend in order to generate a reasonable GARCH trend value starting in 2002.

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Table 4. Compact, significant changes in R&D expenditure, firm performance and earnings risk

	(1) Controls only	(2) Base model	(3) Including earnings underperformance
Intercept	0.14***	0.21**	0.03
	5.35	*7.70*	*1.11*
Compact, significant changes in R&D expenditure		0.001**	0.0005***
		6.95	*2.57*
Firm earnings underperformance relative to industry			4.02***
			23.76
Changes in R&D expenditure * firm earnings underperformance			0.01***
			3.39
Firm size	−0.01***	−0.02***	−0.02***
	−2.90	*−4.71*	*−5.23*
Firm debt	0.69***	0.58***	0.75***
	18.53	*13.96*	*19.15*
Firm profitability	0.00***	0.00***	0.00***
	21.64	*21.02*	*20.33*
Firm R&D intensity	0.38***	0.36***	0.41***
	23.92	*21.26*	*23.51*
Firm industrial diversification	−0.28***	−0.27***	−0.21***
	−12.59	*−12.02*	*−9.54*
Firm growth	0.02***	0.04***	0.04***
	7.69	*8.36*	*9.23*
R-square	0.1416	0.1421	0.1857
F-statistic	373.73***	284.77***	303.14***
Incremental F test		1.00***	70.93***
	n = 11,040	n = 11,040	n = 10,965

We test the impact that significant changes in R&D spending has on firm value and whether firm earnings underperformance relative to industry influences the impact on firm value. t-statistics are in *italics* below parameter estimates.
Firm-level fixed effects are included in all specifications.
*significant at 10%; **significant at 5%; ***significant at 1%.

compact, significant changes in R&D expenditure is shown in column four. The log likelihood ratio indicates that the explanatory power of the specification including compact, significant changes in R&D expenditure (column four) is statistically significantly greater than the controls-only specification (column three). The parameter estimate on compact, significant changes in R&D expenditure is positive and statistically significant. Using new product releases as the dependent variable, we find more evidence that punctuated changes in R&D expenditure are positively related to R&D-related outcomes. This evidence provides further support for Hypothesis 3.

Hypothesis 4 predicts that compact, significant changes in R&D expenditure are positively related to firm performance. The results of the regression analysis testing this hypothesis are shown in Table 4. Column one shows the regression estimates using the base specification. Column two shows the regression estimates including the measure of compact, significant changes in R&D expenditure. Note that the explanatory power of the specification using only control variables shown in column one is statistically significant. An incremental F-test shows that the explanatory power of the specification shown in column two is statistically significantly greater than the controls-only model shown in column one. The parameter estimate on compact, significant changes in R&D expenditure is positive and statistically significant. Hypothesis 4 is supported.

Hypothesis 5 predicts that the relationship between compact, significant changes in R&D expenditure and firm performance is higher among firms that experience more frequent and substantial earnings underperformance relative to their industry peers. This hypothesis can be tested by adding the measure of firm earnings underperformance relative to industry peers and the interaction of significant changes in R&D expenditure and firm earnings underperformance relative to industry peers to the specification presented in Table 4, column two. The results of this regression analysis are shown in column three of Table 4. Once again, the incremental F-test is statistically significant. The parameter estimate on the interaction of compact significant changes in R&D spending and firm risk is positive and statistically significant, which corroborates Hypothesis 5.

Tests of robustness

In the main section of this paper, we have estimated the relationship between compact, significant changes in R&D expenditure and firm innovative output in the year the spending shift occurred and the two years following the shift. The selection of these study windows is *ad hoc*. These test results are robust to selecting different time lags for the R&D change and firm innovative output. For example, we evaluated the relationship between compact, significant changes in R&D expenditure and patented knowledge output using a zero time lag (i.e.—innovative output in the same year the change occurs) and a one-year lag. This empirical finding is consistent with results in the literature where the lag between R&D expenditures and patent output has been reported to be between 0 and 18 months (Blundell, Griffith, and Windmeijer, 2002; Hall *et al*., 1986). We find that our results are robust to changes in the time lag between changes in R&D spending and firm innovative output.

We also evaluate whether compact, significant changes in R&D expenditure are endogenous. We use an instrumental variable (IV) regression model in order to estimate the relationship between compact, significant changes in R&D expenditure and firm performance. The key issue is the selection of instrument(s). In the first stage, our instrumental variable is the size of the firm's Board of Directors. Prior research has shown that team size is an important determinant of decision making (Haleblian and Finkelstein, 1993; Smith *et al*., 1994). For example, smaller groups have fewer points of view, which may lead to faster but less informed decisions. Larger groups must accommodate more points of view, which may lead to slower but more deliberate decisions. In results not shown here, we find that the size of the firm's Board of Directors is a good predictor of compact, significant changes in R&D expenditure. It also has an insignificant correlation with the relevant error terms, ensuring that it is a good instrument. We also find that the stage two results show that the instrumental variable regression coefficient on significant, compact changes in R&D spending is positive and statistically significant. This empirical finding is consistent with the main results in our paper.

CONCLUSION

We began by identifying a fundamental conflict in the existing research on R&D management. There is a broad collection of research suggesting that successful innovation at the firm level requires consistent, sustained R&D investment (Dierickx and Cool, 1989; Grabowski, 1968; Hambrick *et al*., 1983; Kor and Mahoney, 2005). However, another stream of research links innovative performance to a firm's ability to combat successfully R&D project entrenchment (Mudambi and Swift, 2011). We suggest that the long periods of exploitation of extant competencies require stable and consistent R&D investment, while the periods of transition to new competencies require uprooting entrenched R&D interests in the firm. Following this line of reasoning, significant, compact changes in the firm's level of R&D expenditure are evidence that the firm is moving between periods of R&D-based exploitation and exploration. In this paper, we offer evidence that compact, significant changes in firm-level R&D spending is positively associated with shifts between R&D-based exploration and exploitation, with higher levels of R&D-related outputs and with overall firm performance.

These new findings complement several existing perspectives on technology and innovation management. Prior research has suggested that high-performing firms are ambidextrous; that is, they practice both R&D-based exploration and exploitation (Gibson and Birkinshaw, 2004). These findings help us to understand how this is achieved. Firms that are able to time these changes in R&D spending with shifts in their market positions generate superior performance by proactively abandoning the exploitation of prior competencies and discovering new ones at the right times.

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Changes in firm-level R&D spending can occur for many reasons. Firms may reduce R&D spending in order to smooth earnings (Baber *et al*., 1991; Bushee, 1998; Dechow and Sloan, 1991). It is possible that changes occur due to the introduction of new technologies that make R&D more efficient or due to changes in regulations that prohibit or encourage certain types of R&D. However, we believe that the findings in this paper, particularly the results of Hypothesis 1, show that, *ceteris paribus*, firms that make significant, compact changes to R&D expenditure are moving between R&D-based exploration and exploitation.

We also show that such firms create greater firm value as well as superior R&D-related outputs. Our new findings indicate that significant, compact changes in firm-level R&D expenditure are evidence of superior innovation and value creation. We suggest that this link may be caused by firm managers' ability to move from exploitation while the firm possesses commercially valuable competitive advantages to exploration as those competencies wane in value. Therefore, this study identifies a new avenue of research in R&D management. Future research could investigate whether firms that successfully link drastic changes in R&D expenditure to superior firm performance have distinguishing structural characteristics. Case study inquiry can also help us to understand better the processes within the firm that underpin the link between R&D spending changes and firm performance.

While this research provides new insights regarding proactive R&D management, many issues can be addressed in future research. Scholars can advance this work in several ways. Our dataset is constructed using well-known and widely used secondary databases such as Compustat, NBER U.S. Patent Citations Data File, and Lexis-Nexis. While our use of these databases has advantages in terms of comparability with a wealth of previous studies, it has restricted us to using firm-level R&D spending. The use of project-level R&D spending data can advance this line of inquiry significantly. With project-level data, researchers can evaluate whether, during times of significant shifts between R&D-based exploitation and exploration, certain projects are terminated while new ones are initiated. In addition, the specifications used in this paper cannot determine the frequency with which firms make compact, significant changes in R&D expenditure. While we measure simply the largest shift in R&D spending over the study period, we do not detect whether more than one major shift can occur within this time frame.

Schumpeter (1942) maintained that churning the population of firms through creative destruction and macroeconomic volatility are related determinants of economy-wide innovation. These insights reinforce the value of intense interfirm competition as a selection mechanism. We extend the Schumpeterian insight to the intrafirm domain and provide evidence that abrupt changes in R&D expenditure at the firm level can create value. Indeed, the active management of a firm's R&D portfolio seems to appear in the form of intrafirm 'creative destruction' as promising research projects expand at the expense of those with less promise. The effective implementation of such an intrafirm selection mechanism appears to be a competency that underpins both innovative and financial performance.

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REFERENCES

Abramovitz M. 1956. Resource and output trends in the United States since 1870. *American Economic Review* **46**(2): 5–23.

Acs ZJ, Audretsch DB. 1989. Innovation in large and small firms: an empirical analysis. *American Economic Review* **78**(4): 678–690.

Ahuja G, Katila R. 2001. Technological acquisitions and the innovation performance of acquiring firms: a longitudinal study. *Strategy Management Journal* **22**(3): 197–220.

Ahuja G, Katila R. 2004. Where do resources come from? The role of idiosyncratic situations. *Strategic Management Journal* **25**(8–9): 887–907.

Ahuja G, Lampert CM. 2001. Entrepreneurship in the large corporation: a longitudinal study of how established firms create breakthrough inventions. *Strategic Management Journal* **22**(6–7): 521–543.

Almeida P, Kogut B. 1999. Localization of knowledge and the mobility of engineers in regional networks. *Management Science* **45**(7): 905–917.

Anderson P, Tushman M. 2001. Organizational environments and industry exit: the effects of uncertainty,

DOI: 10.1002/smj

munificence and complexity. *Industrial and Corporate Change* **10**(3): 675–711.

Argyres N. 1996. Capabilities, technological diversification and divisionalization. *Strategic Management Journal* **17**(5): 395–410.

Arrow K. 1962. Economic welfare and the allocation of resources for invention. In *The Rate and Direction of Inventive Activity: Economic and Social Factors*. NBER and Princeton University Press: Princeton, NJ; 609–625.

Azoulay P, Ding W, Stuart T. 2009. The effect of academic patenting on the rate, quality and direction of (public) research output. *Journal of Industrial Economics* **57**(4): 637–623.

Azoulay P, Graff Zivin J, Wang J. 2010. Superstar extinction. *Quarterly Journal of Economics* **125**(2): 549–589.

Baber WR, Fairfield PW, Haggard JA. 1991. The effect of concern on discretionary spending decisions: the case of research and development. *Accounting Review* **66**(4): 818–829.

Baird JS, Thomas H. 1990. What is risk anyway? Using and measuring risk in strategic management. In *Risk, Strategy and Management*, Thomas RAB (ed). JAI Press: Greenwich, CT; 21–52.

Barnett WP, Freeman J. 2001. Too much of a good thing? Product proliferation and organizational failure. *Organization Science* **12**(5): 539–558.

Baum JAC, Li SX, Usher JM. 2000. Making the next move: How experiential and vicarious learning shape the locations of chains' acquisitions. *Administrative Science Quarterly* **45**(4): 766–801.

Benner M, Tushman ML. 2003. Exploitation, exploration, and process management: the productivity dilemma revisited. *Academy of Management Review* **28**(2): 238–256.

Berger PG, Ofek E. 1995. Diversification's effect on firm value. *Journal of Financial Economics* **37**(1): 39–65.

Blundell R, Griffith R, Windmeijer F. 2002. Individual effects and dynamics in count data models. *Journal of Econometrics* **108**(1): 113–131.

Bushee BJ. 1998. The influence of institutional investors on myopic R&D investment behavior. *Accounting Review* **73**(3): 305–333.

Califf RM, Zarin DA, Kramer JM, Sherman RE, Aberle LH, Tasneem A. 2012. Characteristics of clinical trials registered in ClinicalTrials.gov, 2007–2010. *Journal of the American Medical Association* **307**(17): 1838–47.

Campa JM, Kedia S. 2002. Explaining the diversification discount. *Journal of Finance* **57**(4): 1731–1762.

Cantwell J, Mudambi R. 2005. MNE competence-creating subsidiary mandates. *Strategic Management Journal* **26**(12): 1109–1128.

Chesher A. 1979. Testing the law of proportionate effect. *Journal of Industrial Economics* **27**(4): 403–411.

Chung KH, Pruitt SW. 1994. A simple approximation of Tobin's q. *Financial Management* **23**(3): 70–74.

Clark KB, Fujimoto T. 1991. *Product Development Performance: Strategy, Organization and Management in the World Auto Industry*. Harvard Business Press: Boston, MA.

Clark KB, Chew WB, Fujimoto T. 1987. Product development in the world auto industry. *Brookings Papers on Economic Activity* **3**: 729–771.

Cockburn I, Henderson R. 1998. Absorptive capacity, coauthoring behavior, and the organization of research in drug discovery. *Journal of Industrial Economics* **46**(2): 157–182.

Cockburn I, Henderson R, Stern S. 2003. Untangling the origins of competitive advantage. *Strategic Management Journal* **21**(10–11): 1123–1145.

Cohen WM, Levinthal DA. 1990. Absorptive capacity: a new perspective on learning and innovation. *Administrative Science Quarterly* **35**(1): 128–152.

Coombs R, Narandren P, Richards A. 1996. A literature-based innovation output indicator. *Research Policy* **25**(3): 403–413.

Cyert R, March JG. 1963. *A Behavioral Theory of the Firm*. Prentice-Hall: Englewood Cliffs, NJ.

Dechow PM, Sloan RG. 1991. Executive incentives and the horizon problem: an empirical investigation. *Journal of Accounting and Economics* **14**(1): 51–89.

Dierickx I, Cool K. 1989. Asset stock accumulation and sustainability of competitive advantage. *Management Science* **35**(12): 1504–1511.

DiMasi JA, Feldman L, Seckler A, Wilson A. 2010. Trends in risks associated with new drug development: success rates for investigational drugs. *Nature: Clinical Pharmacology and Therapeutics* **87**: 272–277.

DiMasi JA, Grabowski HG. 2007. The cost of biopharmaceutical R&D: is biotech different? *Managerial and Decision Economics* **28**(4–5): 469–479.

DiMasi JA, Hansen W, Grabowski HG. 2003. The price of innovation: new estimates of drug development costs. *Journal of Health Economics* **22**(2): 151–185.

Dosi G. 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technological change. *Research Policy* **11**(3): 147–162.

Dunlap-Hinkler D, Kotabe M, Mudambi R. 2010. A story of breakthrough vs. incremental innovation: corporate entrepreneurship in the global pharmaceutical industry. *Strategic Entrepreneurship Journal* **4**(2): 106–127.

Dyer JH. 1996. Specialized supplier networks as a source of competitive advantage: evidence from the auto industry. *Strategic Management Journal* **17**(4): 271–292.

Erickson T, Whited TM. 2000. Measurement error and the relationship between investment and q. *Journal of Political Economy* **108**(5): 1027–1057.

Folta TB, O'Brien JP. 2004. Entry in the presence of dueling options. *Strategic Management Journal* **25**(2): 121–138.

FDA. 1998. *Guidance for Industry: Standards for the Prompt Review of Efficacy Supplements, Including Priority Efficacy Supplements*. Review Management Working Group, Center for Drug Evaluation and Research (CDER) and Center for Biologics Evaluation and Research (CBER), U.S. Food and Drug Administration: Washington, DC.

Gagnon M, Lexchin J. 2008. The cost of pushing pills: a new estimate of pharmaceutical promotion expenditures in the United States. *PLoS Medicine* **5**(1): 29–33.

Gibson CB, Birkinshaw J. 2004. The antecedents, consequences, and mediating role of organizational ambidexterity. *Academy of Management Journal* **47**(2): 209–226.

Gilsing V, Nooteboom B. 2006. Exploration and exploitation in innovation systems: the case of pharmaceutical biotechnology. *Research Policy* **35**(1): 1–23.

Giovannetti GT, Morrison SW. 2000. *Convergence: The Biotechnology Industry Report*. Palo Alto, CA: Ernst & Young.

Grabowski HG. 1968. The determinants of industrial research and development: a study of the chemical drug and petroleum industries. *Journal of Political Economy* **76**: 292–306.

Grabowski H, Vernon J. 1990. A new look at the returns and risks to pharmaceutical R&D. *Management Science* **36**(7): 804–821.

Haleblian J, Finkelstein S. 1993. Top management team size, CEO dominance and firm performance: the moderating roles of environmental turbulence and discretion. *Academy of Management Journal* **36**(4): 844–863.

Hall BH, Griliches Z, Hausman JA. 1986. Patents and R&D: is there a lag? *International Economic Review* **27**(2): 265–284.

Hall BH, Jaffe A, Trajtenberg M. 2001. *The NBER patent citations data file: lessons, insights and methodological tools*. *NBER Working Paper Series*. National Bureau of Economic Research: Cambridge, MA.

Hall BH, Jaffe A, Trajtenberg M. 2005. Market value and patent citations. *Rand Journal of Economics* **36**(1): 16–38.

Hambrick DC, MacMillan IC, Barbosa RR. 1983. Business unit strategy and changes in the product R&D budget. *Management Science* **29**(7): 757–769.

Hansen GS, Hill CWL. 1991. Are institutional investors myopic? A time-series study of four technology driven industries. *Strategic Management Journal* **12**(1): 1–16.

Harryson SJ, Dudkowski R, Stern A. 2008. Transformation networks in innovation alliances—the development of Volvo C70. *Journal of Management Studies* **45**(4): 745–773.

Heckman J. 1979. Sample bias as a specification error. *Econometrica* **47**(1): 153–162.

Helfat C. 1994. Firm specificity in corporate applied R&D. *Organization Science* **5**(2): 173–184.

Henderson R, Cockburn I. 1994. Measuring competence? Exploring firm effects in pharmaceutical research. *Strategic Management Journal* **15**: 63–84.

Hitt MA, Hoskisson RE, Kim H. 1997. International diversification: effects on innovation and firm performance in product-diversified firms. *Academy of Management Journal* **40**(4): 767–798.

Jaffe A. 1986. Technology opportunity and spillovers of R&D: evidence from firms' patents, profits and market value. *American Economic Review* **76**(5): 984–1001.

Klepper S. 1996. Entry, exit, growth and innovation over the product life cycle. *American Economic Review* **86**(3): 562–583.

Kor Y, Mahoney JT. 2005. How dynamics, management, and governance of resource deployments influence firm-level performance. *Strategic Management Journal* **26**(5): 489–496.

Lang L, Ofek E, Stulz R. 1996. Leverage, investment and firm growth. *Journal of Financial Economics* **40**(1): 3–29.

Leonard-Barton D. 1992. Core capabilities and core rigidities: a paradox in managing new product development. *Strategic Management Journal* **13**: 111–125.

Levinthal DA, March J. 1993. The myopia of learning. *Strategic Management Journal* **14**: 95–112.

Lexis-Nexis. 2007. *Lexis-Nexis Academic database*: Reed Elsevier. Available at: http://academic.lexisnexis.com/online-services/academic-overview.aspx (accessed 15 November 2007).

Lilien GL, Yoon E. 1990. The timing of competitive market entry: an exploratory study of new industrial products. *Management Science* **36**(5): 568–585.

Mao JCT. 1970. Survey of capital budgeting: theory and practice. *Journal of Finance* **25**(2): 349–360.

March JG. 1991. Exploration and exploitation in organizational learning. *Organization Science* **2**(1): 71–87.

March JG. 1996. Continuity and change in theories of organizational action. *Administrative Science Quarterly* **41**(2): 278–287.

March JG. 2006. Rationality, foolishness, and adaptive intelligence. *Strategic Management Journal* **27**(3): 201–214.

March JG, Shapira Z. 1987. Managerial perspectives on risk and risk taking. *Management Science* **33**(11): 1404–1418.

McGahan AM, Porter ME. 1997. How much does industry matter, really? *Strategic Management Journal* **18**(Summer Special Issue): 15–30.

Menezes C, Geiss C, Tressler J. 1980. Increasing downside risk. *American Economic Review* **70**(5): 921–932.

Miller D, Friesen P. 1984. *Organizations: A Quantum View*. Prentice-Hall: Englewood Cliffs, NJ.

Miller KD, Leiblein MJ. 1996. Corporate risk-return relations: returns variability versus downside risk. *Academy of Management Journal* **39**(1): 91–122.

Miller KD, Reuer JJ. 1996. Measuring organizational downside risk. *Strategic Management Journal* **17**(9): 671–691.

Minton BA, Schrand C. 1999. The impact of cash flow volatility on discretionary investment and the costs of debt and equity financing. *Journal of Financial Economics* **54**(3): 423–460.

Montgomery C, Wernerfelt B. 1988. Diversification, Ricardian rents, and Tobin's q. *Rand Journal of Economics* **19**(4): 623–32.

Mudambi R. 2008. Location, control and innovation in knowledge intensive industries. *Journal of Economic Geography* **8**(5): 699–725.

Mudambi R, Swift T. 2009. Professional guilds, tension and knowledge management. *Research Policy* **38**(5): 736–745.
Mudambi R, Swift T. 2011. Proactive R&D management and firm growth: a punctuated equilibrium model. *Research Policy* **40**(3): 429–440.
Oriani R, Sobrero M. 2008. Uncertainty and the market valuation of R&D within a real options logic. *Strategic Management Journal* **29**(4): 343–361.
Pakes A. 1985. On patents, R&D and the stock market rate of return. *Journal of Political Economy* **93**(21): 390–409.
PhRMA. 2011. *Pharmaceutical Industry Profile 2011*. PhRMA: Washington, DC. Available at: http://catalyst.phrma.org/wp-content/uploads/fromPhrma/phrma_profile_2011_final.pdf (accessed 7 December 2012).
Porter M. 1985. *Competitive Advantage: Creating and Sustaining Superior Performance*. Free Press: New York.
Roberts PW, Amit R. 2003. The dynamics of innovative activity and competitive advantage: the case of Australian retail banking, 1981 to 1995. *Organization Science* **14**(2): 107–122.
Romanelli E, Tushman ML. 1994. Organizational transformation as punctuated equilibrium: an empirical test. *Academy of Management Journal* **37**(5): 1141–1166.
Rosenberg N. 1990. Why do firms do basic research with their own money? *Research Policy* **19**(2): 165–174.
Rosenkopf L, Nerkar A. 2001. Beyond local search: boundary spanning, exploration, and impact in the optical disk industry. *Strategic Management Journal* **22**(4): 287–306.
Rumelt RP. 1974. *Strategy, Structure and Economic Performance*. Harvard Business School Press: Boston, MA.
Scherer FM. 2001. The link between gross profitability and pharmaceutical R&D spending. *Health Affairs* **20**(5): 216–220.
Schumpeter J. 1942. *Capitalism, Socialism and Democracy* (2nd edn). Harper and Row: New York.
Shan W, Walker G, Kogut B. 1994. Interfirm cooperation and startup innovation in the biotechnology industry. *Strategic Management Journal* **15**(5): 387–394.
Sheremata WA. 2004. Competing through innovation in network markets: strategies for challengers. *Academy of Management Review* **29**(3): 359–377.
Smith KG, Smith KA, Olian JD, Sims HP Jr, O'Bannon DP, Scully JA. 1994. Top management demography and process: the role of social integration and communication. *Administrative Science Quarterly* **39**(3): 412–438.
Solow RM. 1957. Technical change and the aggregate production function: a contribution to the theory of economic growth. *Review of Economics and Statistics* **39**(3): 312–320.
Sorenson O, McEvily S, Rongrong Ren C, Roy R. 2006. Niche width revisited: organizational scope, behavior and performance. *Strategic Management Journal* **27**(10): 915–936.
Standard & Poors. 2009. *Compustat North America*. McGraw-Hill: New York.
Theil H. 1967. *Economics and information theory*. North-Holland: Amsterdam, Netherland.
U.S. Census Bureau. 2002. *1997 Economic Census*. U. S. C. Bureau, Ed. Available at: http://www.census.gov/epcd/www/econ97.html (accessed June 2009) http://www.census.gov/epcd/www/econ97.html (accessed 1 November 2007).
US Patent and Trademarks Office. 2007. *PTMB Products and Services Brochure*. United States Department of Commerce: Alexandria, VA.
Wang HC, He J, Mahoney JT. 2009. Firm-specific knowledge resources and competitive advantage: the roles of economic- and relationship-based employee governance mechanisms. *Strategic Management Journal* **30**(12): 1265–1285.
Wilde J. 2008. A simple representation of the Bera-Jarque-Lee test for probit models. *Economics Letters* **101**(2): 119–121.
Zucker L, Darby M, Armstrong J. 2002. Commercializing knowledge: university science, knowledge capture and firm performance in biotechnology. *Management Science* **48**(1): 138–154.

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