ENTANGLED DECISIONS: KNOWLEDGE INTERDEPENDENCIES AND TERMINATIONS OF PATENTED INVENTIONS IN THE PHARMACEUTICAL INDUSTRY

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Conditionally Accepted at Strategic Management Journal

Keywords: R&D, knowledge, interdependencies, termination, research programs

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This study explores the role of knowledge interdependencies on the termination of patented inventions. Termination refers to the abandonment of inventive efforts that are no longer deemed promising. We argue that high interdependencies between an inventive effort and the other inventions in the same research program will increase the cognitive burden on managers and decrease the likelihood of termination. Further, in the presence of interdependencies, managers are likely to rely on heuristics for termination decisions. We focus on two such heuristics: interdependencies of an invention with those in other research programs and the level of external competition in the research program. We test our hypotheses with longitudinal data on patent terminations through non-payment of renewal fees in the pharmaceutical industry.

"The portfolio problem is completely underestimated
by almost every company in terms of complexity."
– Peter Mueller, Chief Scientific Officer, Vertex Pharmaceuticals[1]

Given the uncertainty involved in early-stage R&D, many firms hold a portfolio of inventive efforts. Most follow a multi-stage process of committing further to or terminating investment in each inventive path, as more information becomes available over time. Along with the initial selection of projects from a pool of opportunities, the decisions to continue or terminate each investment comprise a key competency in managing R&D portfolios. How do firms cope with the challenge of managing R&D portfolios over time, and how do they decide which inventive efforts to continue and which ones to terminate? Studies of R&D project evaluation propose varied approaches to allocate scarce resources to the most appropriate research opportunities for further development (Brunner *et al.*, 2008 provides an excellent review.) These models focus on the measurement of the expected economic value of each opportunity through simple net present value calculations, or more complex real option valuation models (Amram and Kulatilaka, 1999; Dixit and Pindyck, 1994). Other approaches take into account the composition of the overall portfolio to achieve a balanced mix of opportunities of different types to fit their overall strategy (e.g., Wheelwright and Clark, 1992).

This well-established and valuable literature has a key limitation in that none of the proposed approaches fully captures the challenges of portfolio management decisions in the real world. In fact, surveys find important discrepancies between the frameworks that receive the most academic attention and those that are most commonly adopted by the practitioners (Cooper, Edgett, and Kleinschmidt, 2001). A key reason for these discrepancies is that the majority of studies examine continuation or termination decisions in isolation, without considering

[1] Pisano, Fleming & Strick, Vertex Pharmaceuticals (A), HBS Case 9-604-101.

interdependencies. Even studies that have considered interdependencies typically focus on interdependencies in value (such as sharing of complementary assets) and not knowledge interdependencies (e.g., Chan, Nickerson, and Owan, 2007). As Brunner and colleagues (2008: 233) note, "almost all research to date on project and portfolio selection has ignored the interdependence that usually exists between projects…it is extremely difficult to understand the interactions between current projects and future learning and capability development." Part of the reason for this lacuna is the availability of data that would allow researchers to connect these two constructs – interdependence and portfolio decisions.

In this study, we address this issue by focusing on how knowledge interdependencies surrounding an inventive effort influence managers' continuation or termination decisions[2,3]. Prior research suggests that the knowledge interdependencies between inventive efforts could influence the innovation performance of a firm (e.g., Fleming and Sorenson, 2001; Yayavaram and Ahuja, 2008; Yayavaram and Chen, 2015). Following this literature, we characterize a firm's knowledge base as a network of inventions, tied by common knowledge components. In this sense, interdependencies represent the extent to which two inventions build on a shared knowledge base, and capture a firm's revealed beliefs about the underlying structure of relationships (Jain, 2016; Yayavaram and Ahuja, 2008). However, such interdependencies may also mean that parallel research efforts are highly contingent on one another, and adapting the portfolio through the elimination of unsuccessful experiments is not easy or straightforward.

[2] We use inventive effort and invention interchangeably in this paper to refer to a research path that culminates in a patentable idea. We use innovation in a broader sense that includes commercialization of an invention.
[3] In our context, a firm makes a choice between continuing or terminating a given inventive effort, so continuation and termination decisions are mirror images of another. We focus on the termination decisions at a single decision point for each invention.

It is important to note that termination is distinct from success in two important ways. First, an invention that is not terminated is not automatically successful. Assuming that success comes from a commercially viable product launch, an invention must go through multiple years of development and many more gates in order to lead to a successful outcome. Not every continued effort (e.g., patent) yields a successful outcome (e.g., product launch), and a continued invention may be terminated at a later time. As such, while termination may represent a failed research effort for the firm (Khanna, Guler, and Nerkar, 2016), continuation of a research path does not guarantee success. Second, while success may depend on external factors, such as technological and market conditions, the decision to terminate is a firm decision that is made under very high uncertainty. As such, it provides a great opportunity to examine firm policy.

The premise of this study is that managers are boundedly rational yet proactive decision makers that aim to use termination decisions to shape adaptive search (Cyert and March, 1963). Terminations provide an opportunity to restructure a firm's innovation portfolio by adapting to newly acquired information and external conditions. We assume that managers base a termination decision on their best estimate of the expected value of an invention. However, knowledge interdependencies within an invention portfolio increase decision complexity and make it more difficult for boundedly rational managers to evaluate the true value of a given invention, especially with respect to measure outcomes that are hard to measure, such as learning. Next, given the inability to make precise estimates of the inventions' future value, we argue that managers are likely to use heuristics in evaluating interdependent inventions. We examine interdependencies across research programs and the level of external competition as two potential heuristics that influence the termination of interdependent inventions.

The empirical setting for this paper is the pharmaceutical industry. We observe the patent portfolios of 85 pharmaceutical firms between 1985 and 1999. By examining the voluntary termination of patents through non-payment of renewal fees, we take advantage of a unique setting in which we observe termination in early research pipelines. The main findings of this paper are threefold. First, we find that, at a given level of usefulness, interdependencies of an invention with other inventions in the same research program in a firm's portfolio reduce the its likelihood of termination. This finding reveals that knowledge interdependencies play an important role in the termination of inventive efforts, beyond what has been captured in prior work. Second, we find that interdependent inventions have an even lower likelihood of termination when they hold interdependencies across research programs. Last, we find that firms are responsive to external competition in terminations, and when other firms are working in the same research area, the impact of interdependencies on terminations is reduced. We argue that interdependencies across research programs and external competition act as decision heuristics when knowledge interdependencies are high. In general, this study highlights termination of inventions as a deliberate process that is highly influenced by the complexity of knowledge.

We hope to inform the literature on knowledge search and recombination by focusing on knowledge and termination. Prior literature has examined in depth how firms search and recombine knowledge to generate novel outcomes (e.g., Fleming and Sorenson, 2004; Gavetti and Levinthal, 2000; Katila and Ahuja, 2002; Levinthal and March, 1981; Rosenkopf and Nerkar, 2001). In comparison, the process by which firms select among various outcomes of search efforts has been underplayed (Knudsen and Levinthal, 2007). Given that search and selection are essential components of choice (Simon, 1959), a focus on idea generation at the expense of selection might yield an imbalanced view of the process and capabilities leading to innovation (Arora *et al.*, 2009). This study complements the current literature on knowledge search and recombination by focusing on the process by which firms screen innovative ideas and shape their portfolios of knowledge.

INTERDEPENDENCE AND R&D AS SEARCH

Interdependence refers to interactions between components of a system such that the value of a particular component depends on the others (Levinthal, 1997), and changes to a component necessitate changes in other components as well (Ulrich, 1995). Interdependencies are often manifest as complementarity, in which "doing more of one thing increases the returns to doing more of another" (Milgrom and Roberts, 1995: 181). Interdependencies may also generate negative externalities between components. The precise nature of the interdependencies may change in intensity or direction at different levels of their interaction, or in the presence of other interdependent components. More importantly, the true nature of interdependencies is often unknown to the boundedly rational managers (Ethiraj and Levinthal, 2004b; Ghemawat and Levinthal, 2008).

Our examination of the relationship between knowledge interdependencies and termination of inventive efforts builds upon research on knowledge search and recombination and on complexity in innovation, as we detail below. We also briefly discuss the treatment of portfolio interdependencies in the corporate strategy literature.

Research on search and innovation in complex systems provides an important building block of this study by providing an understanding of inventive activity. The canonical depiction of search in innovation is as a process of experimentation through recombination of familiar and new components over time (Fleming and Sorenson, 2001; Fleming and Sorenson, 2004;

Schumpeter, 1934). This process is complicated by at least two interrelated aspects. First, the number of potential recombinations of even a small number of components can become extremely large (Fleming and Sorenson, 2001). This makes it impossible for managers to comb through the whole universe of possible recombinations, given the cognitive and resource constraints. Second, interdependencies among knowledge components compound the difficulty of this task, since they further tax the cognitive capabilities of boundedly rational managers (Ethiraj and Levinthal, 2004a). Inventive efforts, therefore, comprise a good example of complex systems characterized by a large number of interdependent components (Simon, 1962). Decision making under such complexity is often characterized as a search for solutions on a multidimensional problem terrain (Levinthal, 1997). In our setting, each useful invention corresponds to a solution, or a peak in the technological landscape (Fleming and Sorenson, 2001; Kauffman, Lobo, and Macready, 2000; Yayavaram and Ahuja, 2008). Value or usefulness of an invention is typically characterized by its subsequent use as a building block for future inventions (Fleming and Sorenson, 2001; Yayavaram and Ahuja, 2008).

The current study contributes to this perspective in several ways. First of all, it is one of the few studies that examine the implications of interdependencies among knowledge components for innovation rather than for product architectures or organizational structures (Fleming and Sorenson, 2001; Yayavaram and Ahuja, 2008; Yayavaram and Chen, 2015). Second, while earlier studies have typically focused on performance outcomes of knowledge interdependencies, to the best of our knowledge, our study is the first one to explore their impact on decisions to terminate individual inventions. Therefore, it provides a rare opportunity to examine an intermediate outcome that influences the performance of adaptive search.

Research in the economics tradition has also investigated the implications of interdependencies across inventions (Choi and Gerlach, 2014, 2017; Fershtman and Kamien, 1992; Gilbert and Katz, 2011). These studies typically examine the cases of complementary innovations that span inventive efforts across multiple firms, as in complex product systems (Ethiraj, 2007). They then explore the competitive implications of interdependent patent portfolios through formal models. Our study is distinct in that we focus on interdependencies within a firm's own research portfolio, and their implications for terminations.

Our research echoes prior work in the corporate strategy literature on the impact of interdependencies on divestitures. For instance, Li and Chi (2013) have used a real options lens to highlight the importance of portfolio focus and diversity in venture capital investments, and Vassolo, Anand, and Folta (2004) have suggested that technological distance from the rest of the portfolio could influence dissolutions of a given alliance. Moreover, recent work suggests that interdependencies of routines among existing business units may increase the operational costs of divesting a business unit (Chang and Singh, 1999; Feldman, 2013; Karim, 2006; Natividad and Rawley, 2015). While the former set of studies focus on portfolios of external arrangements, such as venture capital and alliances, the latter focus on divestitures of divisions or business units. There are potentially important differences between operational interdependencies discussed in these studies and knowledge interdependencies within a research portfolio. For instance, shared operational routines are likely to be minimal and resource dependence dynamics less pronounced in the case of knowledge interdependencies. At the same time, knowledge interdependencies may cause important path dependencies in how firms search and recombine knowledge, and influence how effectively firms learn from past experiences (Levinthal, 1997;

Rivkin, 2000). A study of knowledge interdependencies and terminations of inventive effort could, therefore, yield different effects in substance and magnitude.

Armed with this background, we now turn to a discussion of how interdependencies in an R&D portfolio could play a role in decisions to continue or terminate a specific inventive effort.

Interdependence and Termination of Inventive Efforts

Termination decisions in portfolio management require detecting cues about the prospects of each inventive effort and acting on them. The content of the information may unveil deterioration in the value of an invention to a firm due to exogenous developments in science or technology, new competition, or changes in demand, or due to endogenous causes, such as a failure in project execution. Alternatively, a change in the firm's overall research direction may necessitate termination by decreasing the firm-specific value of the invention. Regardless of the underlying cause, termination of an inventive effort is an adaptive response that requires managers to process and act on new cues.

Interdependencies between inventions may make it difficult to act on such feedback, however. Interdependence increases complexity (Simon, 1962), which taxes managers' cognitive capabilities and their comprehension of cues, and makes it difficult for boundedly rational managers to grasp the underlying causal relationships (Ethiraj, Ramasubbu, and Krishnan, 2012; Fleming and Sorenson, 2001; March and Simon, 1958). In the presence of interdependencies, it is more challenging to anticipate the potentially cascading consequences of a change in one component of a complex system on all the other components (Ulrich, 1995), since the nature of interactions between the components is poorly understood (Ethiraj and Levinthal, 2004a). As a result, interdependencies may make it harder for firms to isolate a single inventive effort for termination. This could challenge the usefulness of multi-stage investment strategies, since adaptation through termination decisions cannot be implemented (Adner and Levinthal, 2004).

In the R&D context, managers may be concerned about terminating a particular inventive effort for several reasons. First, terminated efforts may embody knowledge that may be valuable for the remaining inventions in the firm's portfolio. To the extent that this knowledge is no longer accessible to the inventors in the firm, concurrent or subsequent inventive effort could be hurt. In the longer term, the absorptive capacity of the firm may be harmed due to the loss of a critical piece of interdependent knowledge (Cohen and Levinthal, 1990). Moreover, if inventors perceive terminations as a signal of the firm's research direction (Ethiraj and Zhao, 2010), they may steer away from the underlying research, closing out possibilities of further recombinations. Second, owning interdependent innovations may enable the firm to appropriate higher returns from their R&D investments ex-post (Arora, Fosfuri, and Gambardella, 2001; Choi and Gerlach, 2017; Girotra, Terwiesch, and Ulrich, 2007; Teece, 1986). Removing inventions from the portfolio may then reduce the firm's ability to defend products from the competition.

To the extent that the managers are unsure about the impact of a single termination on the expected value of the portfolio, they may refrain from termination decisions. To complicate the problem, the nature and extent of interdependencies may not be fully visible to managers until after the termination. Managers may sense that their firm could suffer performance losses if they disturb the internal fit between components by making a change in a single interdependent component (Kauffman, 1993; Levinthal, 1997; Rivkin, 2000), but not effectively estimate the nature and extent of those losses. These possibilities may deter managers from terminating inventive efforts even when the usefulness of the particular invention is subpar.

Hypothesis 1: As the interdependence of an invention with the firm's other inventions in the same research program increases, the likelihood of the termination of the focal invention decreases.

Interdependencies Across Research Programs and Termination

When managers' cognitive limitations prevent them from making accurate estimations of the expected value of an inventive effort, they are likely to use heuristics in culling inventions (March and Simon, 1958). Heuristics are simple rules-of-thumb that help managers to organize knowledge in the face of high cognitive complexity and provide guidelines for action (Bingham and Eisenhardt, 2011; Newell and Simon, 1972). Scholars have characterized strategy and R&D processes as combinations of search heuristics (Nelson and Winter, 1977; Rivkin, 2000). Consistent with a growing literature, our perspective of heuristics is not as dysfunctional decision patterns, but as simplified rules that help firms satisfice on decision tasks (e.g., Bingham and Eisenhardt, 2011; Nelson and Winter, 1977; Newell and Simon, 1972).

Given the challenge of disentangling interdependent inventions, it is reasonable to expect managers to employ heuristics in complex termination decisions, as they do in search. Heuristics are especially likely to be helpful when the exact intrinsic value of an invention is hard to assess due to knowledge interdependencies. One such heuristic that may indirectly influence the termination decision has to do with interdependencies that cut across multiple research programs. Inventions that have interdependencies across research programs (along with interdependencies within a research program) may represent boundary-spanning knowledge (Rosenkopf and Nerkar, 2001). Managers may prefer to retain boundary-spanning inventions for several reasons. First, even when the expected value of an invention is hard to gauge due to knowledge interdependencies, inventions that span across research programs are more likely to offer higher value due to fungibility and economies of scope (Anand and Singh, 1997). The knowledge contained in a boundary-spanning invention is likely to be useful in multiple research programs, and knowledge can be shared across multiple programs without loss of value (Arora *et al.*, 2001; Henderson and Cockburn, 1996). Second, research that cuts across division and organizational boundaries is on average more novel, innovative, and likely to result in breakthroughs (Fleming and Waguespack, 2007; Rosenkopf and Nerkar, 2001; Uzzi *et al.*, 2013), even though it has higher variance in outcomes (Leahey, Beckman, and Stanko, 2017; Singh and Fleming, 2010). Given the higher likelihood of a future breakthrough, and in the absence of invention-specific knowledge, managers may refrain from prematurely terminating such inventive paths. Third, many organizations may have in place rhetoric and norms that encourage boundary-spanning research (Leahey *et al.*, 2017), and as such, managers may avoid or delay terminating such inventions in order to signal their support for them. Encouraging boundary-spanning research may especially be important since the difficulties of initiating and engaging in boundary-spanning research are well-documented (Bechky, 2003; Tortoriello and Krackhardt, 2010). Last, the consequences of terminating interdependent and boundary-spanning research may reverberate across the organization, leading to even larger unexpected negative outcomes, such as disrupting current inventive efforts of scientists, derailing learning outcomes and slowing the accumulation of absorptive capacity in multiple areas. Especially given that any single manager may lack the knowledge to evaluate an inventive effort that spans multiple areas, managers may delay or avoid postponing boundary-spanning research efforts as a heuristic.

While it is possible that the first order effect of boundary spanning on termination will be negative for these reasons, we maintain that the main criterion for any termination decision is the expected value of an invention to the firm. When the value is more easily ascertained, managers may not have to resort to heuristics in termination (e.g., Rivkin, 2000). However, when knowledge interdependencies are high and the resultant complexity is too high for boundedly rational managers, we expect to clearly observe the influence of this heuristic on terminations.

Hypothesis 2: All else equal, as the interdependencies of a patent with the other research programs in a firm's portfolio increases, the negative relationship between an invention's interdependencies within its research program and its likelihood of termination will be stronger.

External Competition and Termination

Next, we argue that the extent of competition in a research program may also act as a heuristic in termination decisions when complexity is high due to knowledge interdependencies. Prior literature suggests that research that incorporates knowledge that is new to the world is more likely to result in more radical innovations (Ahuja and Lampert, 2001; Dewar and Dutton, 1986; Eggers and Kaul, 2017). Practitioners are also often encouraged firms to look for areas with little or no competition, rather than settling for a fraction of the profits available in a crowded competitive space (e.g., Kim and Mauborgne, 2005). As a result, managers may refrain from terminating inventive efforts in novel areas with little or no competition, given the higher potential for a breakthrough and a higher share of the potential profit. Conversely, given the reduced expected returns in areas where competition is higher, managers may be more willing to terminate interdependent experiments, all else equal. For instance, in pharmaceuticals, cardiovascular and anti-infective drugs represent crowded markets in which firms face reimbursement pressure and generic competition, which reduces the incentives to invest (Kaitin and DiMasi, 2011). In addition, new areas are where firms can stake their claims and signal their preemptive motives (Clarkson and Toh, 2010). Prior research suggests that, in the presence of complementary innovations, firms are particularly likely to crowd toward similar inventions for preemptive reasons (Choi and Gerlach, 2014, 2017). If managers sense that a firm can get there first, they may opt to maintain patents to preempt entry and limit future competition. Moreover, given that areas of exploration with little competitive activity and are poorly understood, managers may avoid early termination of interdependent innovations because the amount of information required to evaluate such inventions is simply not available at early decision points.

In sum, we argue that the lack of competition in a research area may act as a heuristic to delay or avoid termination, given the potential upside of novelty, the level of uncertainty, and preemptive motives. As in our earlier arguments, we expect firms to use this heuristic more intensely when there is more uncertainty about the value of any individual inventive effort; as a result, we expect competition to be more impactful on terminations decisions when knowledge interdependencies are high, all else equal.

Hypothesis 3: All else equal, as the number of competitors in a specific a research program increases, the negative relationship between interdependencies and termination will be weaker.

CONTEXT: PHARMACEUTICAL DRUG DISCOVERY

We provide an empirical test of our hypotheses in pharmaceutical drug discovery. This area provides an appealing context to examine termination of inventive efforts for several reasons. First, the industry is highly research-intensive (Henderson and Cockburn, 1994). Prior research reports that patented inventions represent the majority of the innovative activities in this industry (e.g., Grabowski and Vernon, 1992; Levin *et al.*, 1987). Patenting occurs at a higher rate (Arundel and Kabla, 1998; Chandy *et al.*, 2006; Cohen, Nelson, and Walsh, 2000; Paruchuri, Nerkar, and Hambrick, 2006) and starts earlier in research than in most other industries, long before tangible product outcomes (Lehman, 2003). This allows us to track inventive efforts in pharmaceutical research portfolios in a relatively comprehensive manner, and to observe the trajectories of innovation from early on in the process. Our study focuses on the research phase of pharmaceutical R&D, where firms search for chemical compounds that can then be the foundation of drug development (Henderson and Cockburn, 1994).

Second, given the low likelihood of achieving a commercially viable drug (DiMasi *et al.*, 2010; Pisano, 2006), pharmaceutical firms typically file for and hold a large portfolio of patents at any given point in time. These portfolios comprise a nested structure of inventive effort at different levels, which makes them an excellent example of recombinant research (Fleming and Sorenson, 2001; Fleming and Sorenson, 2004; Schumpeter, 1934). It is possible to conceive of the human metabolism as a complex system with poorly understood interdependencies that are the target of pharmaceutical research. First-level components of that system are the research programs that represent therapeutic (disease) areas such as diabetes therapy or cardiology (Henderson and Cockburn, 1996). Research programs also reflect the internal organization of research within pharmaceutical firms, as they influence the boundaries of research and communication flows between research teams (Henderson and Cockburn, 1996; Henderson and Clark, 1990). Research under each program houses multiple patented inventions. We refer to each of these patented ideas as a specific invention, a building block for a larger project. In turn, each patented invention is often characterized as a recombination of multiple knowledge components (e.g., Fleming and Sorenson, 2001). In this way, pharmaceutical drug discovery exemplifies a hierarchical complex system that is composed of a succession of interrelated subsystems with their own subsystem (Sanchez and Mahoney, 1996; Simon, 1962).

Third, the industry provides an appealing context to study knowledge interdependencies between inventions in a portfolio. As the above discussion reveals, simultaneous research efforts within a firm may have underlying knowledge components in common. Building on prior research that measures interdependencies through common knowledge components (e.g., Fleming and Sorenson, 2001; Sorenson, Rivkin, and Fleming, 2006), we are able to trace and measure the extent of interdependencies between inventive efforts. Moreover, since pharmaceutical firms typically undertake inventive efforts in multiple therapeutic areas, we are able to consider interdependencies within and across therapeutic areas. This gives us a unique opportunity to understand how interdependencies influence the management of research portfolios at a given level of individual patent performance.

Finally, the drug discovery and development process has distinct stages at which firms choose to pursue or terminate inventive efforts. Apart from the FDA-enforced clinical trials, pharmaceutical firms must pay renewal fees to maintain their intellectual property rights on each patent at 4-, 8-, and 12-years after the grant date (Harhoff *et al.*, 1999; Lanjouw and Schankerman, 2004; Moore, 2005; Serrano, 2010). Given the large upfront outlays in research, low costs of renewal, and alternative means of deploying patents such licensing and sales, termination of a patent represents a deliberate decision to terminate a research path[4] (Appendix 1 provides a detailed review of the literature on patent terminations). In fact, as opposed to clinical trials, which often occur much later in the discovery and development process, and are typically terminated due to exogenous failures in trial outcomes (Arora *et al.*, 2009), patent terminations

[4] In this paper, we use termination to refer to the firm giving up the intellectual property rights on a patented invention through non-payment of periodic renewal fees. This is distinct from expirations that occur at the end of the 20-year patent term, and abandonments at the application stage.

provide an earlier and more comprehensive window into deliberate adaptive responses in the pharmaceutical industry (DiMasi, 2001; Khanna *et al.*, 2016). According to Ding *et al.* (2014), compounds in the preclinical stage comprise about half of all pharmaceutical research. Moreover, early terminations are important to contain the high development costs in the pharmaceutical industry, where failures in late-stage trials are extremely costly: "if a drug is going to fail, it should fail quickly" (Shillingford and Vose, 2001: 942).

METHODS

Data

Our analysis combines the data on termination of inventions, characteristics of research programs in a firm's research portfolio, and competitive landscape in the pharmaceutical industry. We first compiled all patents categorized in United States Patent and Trademark Office (USPTO) patent classes 424 and 514 (drug, bio-affecting and body treating compositions) between 1985 and 1999. This led to a total of 100,065 patents that belonged to more than 200 firms. Since we are interested in firms that engage in formal R&D, we removed firms that did not patent for at least five consecutive years in the study period (Cuervo‐Cazurra and Un, 2010). Also, many of these patents only had a minor application in pharmaceutical industry and were focused on knowledge areas outside pharmaceuticals. Therefore, we removed patents with a primary class other than 424 or 514 to be certain that our sample focused on inventions within the pharmaceutical industry. These two steps reduced the sample size to 8,256 patents owned by 102 firms. After accounting for missing values of variables used in this study, empirical models are based on 7,124 patents for 85 firms.

Variables

We measure termination of inventive efforts using the termination of pharmaceutical patents through a failure to pay renewal fees four years after the grant date. Based on the discussion in the prior section and Appendix 1, and following prior work (Khanna *et al.*, 2016; Serrano, 2010), it is our contention that terminations represent deliberate terminations by firms, and firms commit resources to identifying and terminating less valuable patents as a part of their portfolio management strategy[5]. We collect patent termination data from the USPTO, which provides detailed information on patents that are terminated due to nonpayment of maintenance fees. We only focus on terminations at the 4-year mark in order to capture the early phases of research, and limit heterogeneity in the nature and motives for terminations that may arise at later decision points. The dependent variable, patent termination, is binary and is coded as one if a patent got terminated four years after grant date and zero otherwise. Of the 7,124 patents in our sample, approximately 19 percent were terminated four years after the grant date.

The independent variable is the interdependence of the focal patent with the other patents in the same research program within the firm's research portfolio. We define research programs based on the classification created by IMS Health. IMS Health's Uniform System of Classification (USC) classifies pharmaceutical drugs into 34 therapeutic categories, such as analgesics, anti-obesity, and respiratory therapy, which we use to identify research programs. Table 1 presents the codes and descriptions of these 34 categories. The USPTO, however, does not categorize patents into same categories and instead assigns subclasses to each patent (>2,000 subclasses in the pharmaceutical industry). With the help of a trained expert in pharmacology, we map the USPTO-assigned subclasses onto USC's 34 categories (a detailed concordance

[5] It is possible that a firm fails to renew a patent out of neglect rather than deliberate motives. These can be reversed within a set grace period, and such patents will be renewed after a short lapse if important to the firm. We remove those from our consideration set in the empirical analysis to capture deliberate terminations.

matrix that connects the USPTO classes to the IMS Health categories is available from the authors). We then identify the key research program for each patent based on the highest number of subclasses of a patent that map onto a USC category. For example, if three of the five subclasses of a patent map onto USC category 9, the patent is assigned to that category. In a few cases where there is no dominant category, we use the first subclass that appeared in the patent to identify the USC category. Patents in a firm's portfolio that belong to the same therapeutic area comprise the firm's research program in that area.

Table 1 around here

After assigning each patent to a research program, we calculate our independent variable, i.e. *interdependence of the patent within its research program*. The premise behind the interdependence measure for a patent is that subclasses assigned to a patent represent the knowledge components comprising the patent, and the extent of shared knowledge components between two patents represents their interdependence (Fleming, 2001; Fleming and Sorenson, 2004; Ganco, 2013). Following tradition, we create a network of patents within a research program in each firm using subclasses as nodes and common patents as edges. Next, we take the average of the degree centralities of the subclasses underlying a patent to estimate the interdependence of the patent with all the other patens in the same research program. The measure essentially captures how frequently subclasses that are part of a patent are combined with subclasses of other patents in the same research program. Higher interdependence of a patent indicates that its subclasses are combined more frequently with the other subclasses in the research program. The steps to calculate interdependence can be summarised mathematically:

$$II_{a,i,j} = \frac{\sum_{x \in a} centrality\ of\ x\ in\ network\ of\ patents\ in\ firm\ i\ and\ research\ program\ j}{count\ of\ subclasses\ of\ patent\ a} \quad (1)$$

where $II_{a,i,j}$ is interdependence of patent a in firm i in research program j with other patents in research program j. The numerator in equation (1) is the sum of centralities of subclasses (x) that are assigned to patent a in the network of patents in research program j in firm i. The denominator is the count of subclasses of patent a.

The first moderating variable used in this study is *interdependence across research programs,* i.e., interdependence of a given patent in a research program with patents that are in the other research programs in the firm's portfolio. The measure is constructed using the same methodology, except patents that are considered to construct the network are different. Mathematically, it can be described as:

$$IO_{a,i,j} = \frac{\sum_{x \in a} centrality\ of\ x\ in\ network\ of\ patents\ in\ firm\ i\ and\ outside\ research\ program\ j}{count\ of\ subclasses\ of\ patent\ a} \quad (2)$$

where $IO_{a,i,j}$ is interdependence of patent a in firm i in research program j with patents outside research program j. The measure captures the extent to which knowledge components (captured by subclasses) of patent a are combined with subclasses of patents in other research programs. We then calculate the average interdependence of all patents within a research program to arrive at our measure.

The second moderating variable is the *extent of external competition*, which we measure as the number of other firms that have at least one patent in the same therapeutic area as the focal patent. The measure is weighted by number of each firm's patents in the same therapeutic area to account for the size of each competitor in the area. Formally:

$$C_{a,i,j,k} = \frac{\sum_{j \in a} number\ of\ firms\ with\ k\ patents\ in\ research\ program\ j \times k}{\sum number\ of\ firms} \quad (3)$$

$C_{a,i,j,k}$ in equation (3) measures the extent of competition for patent a in firm i and research program j. The equation (3) shows the weighted sum of the number of firms in our sample that have at least one patent in research program j of patent a, with weights as the number of each firm's patents ($= k$) in research program j. We interact these two measures with a patent's interdependence within its research program to test our hypotheses.

We also include several control variables that can affect our outcome variable. First, we control for the number of forward citations received by each patent at the year of renewal or termination, since prior work has found that patents with more citations are not only more valuable to firms (Jaffe, Trajtenberg, and Henderson, 1993; Pavitt, 1988; Trajtenberg, 1990), but are also less likely to be terminated (Serrano, 2010). Previous research has shown that number of claims on a patent indicates the number of novel contributions the patent makes and can be a significant predictor of the future value of the patent (Lanjouw and Schankerman, 2004; Tong and Frame, 1994). Since valuable patents are less likely to be terminated, we control for the number of claims for each patent. At the research program level, we control for the main effects of interdependence with other research programs and the extent of external competition.

We control for time-invariant firm properties that may influence termination with firm fixed effects. Additionally, we control for several time-varying firm-level properties. Prior literature has shown that firms that diversify into multiple technologies benefit from technological spillovers, buffer themselves against the risk of investments in a single technology, and get exposed to new opportunities and innovation (Jaffe, 1986; Nelson, 1959). Therefore, by strategically undertaking ideas in technologically diverse areas, firms can change their decision to terminate inventions that are under consideration (Li and Chi, 2013). We control for technological diversity as the Herfindahl Index for subclasses in which a firm patented in a given year. Next, firms conducting R&D across multiple countries can access and leverage resources that are not available in the home country (Kobrin, 1991). Thus, we control for the number of countries in which firms in our sample filed patents. A firm's decision to terminate a project could be endogenous to the way it conducts R&D. It is possible that some firms generate more patents and terminate more of them. Empirically, we account for this by controlling for productivity, the number of patents granted to each firm. A firm's decision to terminate a patent in a research program may be influenced by its existing R&D capabilities in that program (Cohen and Levinthal, 1990). Therefore, we controlled for the stock of the firm's patents within each program. Last, we control for the number of alliances that firms made in a given year, since firms' decisions to enter into an alliance, especially in a high technology industry, are often driven by their strategy to enhance their R&D capabilities (Sampson, 2007) and can potentially influence their decision to terminate patents. All control variables, except those at the patent level, are measured using a 3-year moving average window (t-3 to t-1) to smooth out sharp changes and control for lasting effects. We also included year dummies in the model to control for time-specific trends in the data.

Empirical Approach

In our sample, each observation represents a patent, and the dependent variable, termination, takes the value of one if the patent is terminated four years after grant date and zero if it is renewed. A logit model is a natural choice when the dependent variable is binary. The model estimates the probability that a patent will be terminated as a function of a series of independent, moderating, and control variables with the form:

$$P_{a,i,j,t} = \frac{e^{\beta_1 X_{a,i,j,t-1} + \beta_2 C_{a,i,j,t-1} + \beta_3 C_{i,t-3-t-1}}}{1+ e^{\beta_1 X_{a,i,j,t-1} + \beta_2 C_{a,i,j,t-3-t-1} + \beta_3 C_{i,t-3-t-1}}} \quad (4)$$

$P_{a,i,j,t}$ in equation (4) is the probability that patent a in research program j in firm i will be terminated. $X_{a,i,j,t-1}$ is the vector of independent and moderating variables including interdependence of a patent within a research program, interdependence across research programs, and extent of competition for patent a in research program j in firm *i* in year *t-1*. Independent and moderating variables are measured in *t-1* to avoid simultaneity in the regression equation. $C_{a,i,j,t-3-t-1}$ consists of control variables that are at the patent level and include number of citations and claims for patent a in research program *j* in firm *i*. $C_{i,t-3-t-1}$ is a matrix of control variables at the firm level and consists of technological diversity, number of countries, productivity, and number of alliances for firm i, measured as moving average of values of these variables between *t-3* and *t-1*. The model includes fixed firm and year effects. We conducted a Hausman test to identify the preferred model between fixed effects and random effects, and *p-value (= 0.017)* from the Hausman test suggested the use of a fixed effects model.

Table 2 around here

RESULTS

Table 2 presents the descriptive statistics and correlation matrix for variables used in this paper. The correlations are within acceptable range and indicate no concern for multicollinearity. Table 3 summarizes the results from our fixed-effects logistic models. Model 1 in Table 3 contains only control variables. The coefficient on productivity is positive and has a p-value of 0.007, suggesting that a patent is more likely to be terminated when the firm has acquired more patents in the previous period. Also, the number of citations to a patent decreases the likelihood that a patent will get terminated, although the effect is weak.

Table 3 around here

In Hypothesis 1, we predicted that a patent's likelihood of termination would decline with an increase in its interdependence with the other patents in the same research program. Model 2 in Table 3 tests this relationship. The coefficient of interdependence within the research program is -3.16 at a p-value of 0.010, indicating a considerable decrease in likelihood of termination of a patent with an increase in interdependence. A one standard-deviation increase in a patent's interdependence within the research program (=0.039) decreases the odds of patent termination by 4 percent. We therefore find support for Hypothesis 1.

Hypothesis 2 predicted that interdependence across research programs would exacerbate the relationship between interdependence of a patent within the research program and the patent's probability of termination. The coefficient on the interaction term is negative with a p-value of 0.09 in Table 3, Model 3. To better understand the moderating role of interdependence across research programs, we used the "margins" command in Stata to plot the relationship between interdependence within a research program and predicted probability of a patent's termination at different levels of interdependence (minimum = 0, mean = 0.015, and mean + one standard deviation =~ 0.03) across research programs. As almost 98 percent of the values of interdependence within a research program fall between 0 and 0.1 in our sample, we used this range to plot the relationship. As shown in Figure 1, the likelihood of a patent's termination decreases at a faster rate at higher values of interdependence across research programs. When the interdependence across research programs is zero, there is a decrease in the probability of a patent's termination from 12 percent to 10 percent as the interdependence within the research program increases from 0 to 0.1. When interdependence across research programs is at one standard deviation above the mean, the probability of a patent's termination decreases from approximately 12 percent to 5 percent for the same increase in the interdependence within the research program. In addition, we find that the main effect of the interdependence of the patent across research programs is not significant, suggesting that it acts as a heuristic only in the presence of interdependencies within the research program.

Figures 1 and 2 around here

Results from Model 4 in Table 3 provide support for Hypothesis 3, which predicts that the extent of external competition in the therapeutic area of the focal patent will attenuate the relationship between a patent's interdependence within the research program and its likelihood of termination. The coefficient on the extent of competition is positive (0.39) at a p-value of 0.014. Figure 2 presents the plot of the relationship between predicted the likelihood of termination of a patent and its interdependence within the research program at different levels of competition (minimum = 0, mean =25.8, and mean + standard deviation=68). When there is no competition, the probability of termination of a patent decreases from 25 percent to 14 percent as the interdependence within the research program increases from 0 to 0.1. When the competition is at one standard deviation above the mean, for an equal increase in interdependence within a research program, the probability of termination of a patent decreases from 23 percent to 17 percent. These results indicate that at higher levels of competition, the negative relationship between interdependence and termination is weaker, supporting Hypothesis 3. An interesting result is that when interdependence within a research program is below a certain value (<0.03), firms are more likely to give up a patent when competition is at a minimum. This could reflect termination of ad hoc research outcomes in areas with no interdependencies and no competition, as a result of a low likelihood of leading to a promising drug. At low levels of interdependencies, when it is relatively easier to evaluate value of projects independently, firms may have a higher tendency to terminate experiments in such areas. In addition, we find that the main effect of competition is not significant, consistent with our proposed mechanism of the importance of heuristics under complexity.

Tables 4 and 5 around here

Robustness Analyses

An important alternative explanation for our results is that interdependent inventions represent learning outcomes and not complexity, as we have suggested. If firms gain absorptive capacity by searching in interdependent areas, their termination patterns may reflect superior learning. Similarly, competitors may represent a higher collective knowledge accumulation in an area, so that firms can learn vicariously from competitors (Krieger, 2017). In order to examine this alternative explanation, we generated an interaction term between a firm's past patent stock in a given research program and the level of interdependencies. The firm's patent stock in a research program is an indicator of knowledge accumulation in that program, especially given the widespread practice of patenting in pharmaceuticals. If indeed absorptive capacity increases through interdependent research activity, and influences terminations due to a superior understanding of underlying linkages, this interaction term should have a significant impact on termination. As we present in Table 4, Models 1 and 2, we do not observe a significant interaction between the firm's patent stock in a research program and interdependencies. In addition, we do not observe a significant main effect of the firm's patent stock in a research program on terminations, either. These findings suggest that the knowledge accumulation through directed effort may not be underlying our results. Moreover, our results are robust to the introduction of this interaction effect. Given that learning from other firms' experience is typically harder than learning from a firm's own experience, especially in the presence of complexity (Rivkin, 2000; Winter and Szulanski, 2001), we conclude that the results are unlikely to reflect vicarious learning as well. As an additional robustness test to distinguish between competition as a heuristic and as a tool for vicarious leaning, we removed the weighting of the competition variable by the number of each firm's patents in order to avoid capturing knowledge accumulation instead of competition. Models 3 and 4 in Table 4 show that the results are generally robust, providing further support for our arguments. These results could reflect the possibility that learning is challenging and absorptive capacity is hard to build under interdependencies, but require further research that is beyond the scope of this study.

Second, since it is possible that termination decisions in the same research program or firm portfolio are not independent, we investigated whether the observed relationships between interdependence and termination hold if we move the unit of analysis to research programs and firms. First, we modified the dependent variable to reflect the number of patents terminated in a research program by a firm in each year. The independent and moderating variables are calculated as averages of patents' interdependencies within each research program, across research programs, and the level of competition in a given research program each year. The control variables, number of citations and claims, are also the averages of values for all patents in the research program. Other research program and firm-level control variables are the same as in the main analysis. We used negative binomial models with fixed effects since the dependent variable is a non-negative integer. Table 5, Models 1 and 2 present the results. We then repeated a similar analysis at the firm level rather than the program level. The results are presented in Models 3 and 4 in Table 5. The findings are consistent with those obtained in hypothesis tests. Interestingly, we observe in this model that the main effect of competition is positive and significant, along with the interaction effect between competition and interdependencies. This could suggest that firms may be more likely to give up clumps of interdependent knowledge under conditions of competition and complexity.

In unreported results, we also tested whether the relationship between interdependence and termination is curvilinear. We did not find evidence for a curvilinear relationship within the range of observed variables in our data set.

DISCUSSION AND CONCLUSIONS

This study generated several interesting insights. The results suggest that inventions with higher value are less likely to be terminated, supporting our expectation that termination is a deliberate process that firms use as a lever in managing the innovation process. Controlling for the value of an invention, we find that interdependencies between the invention and others in the same research program influence whether the invention is likely to be terminated or not. This result points to the challenge of evaluating the value of an individual invention for the overall research endeavor in the presence of interdependencies. Moreover, we find that interdependencies across research programs exacerbate this effect, and competition in the research program attenuates it. We attribute these findings to heuristics managers use in evaluating interdependent inventions.

Our study contributes to the literature on knowledge search and recombination by highlighting that termination decisions are far from straightforward. Compared to the research on the processes of search and recombination, selection and termination have so far received less attention in the literature (Knudsen and Levinthal, 2007). However, as prior research also notes, search and selection are capabilities that are both required for successful management of innovations (Adner and Levinthal, 2004; Arora *et al.*, 2009). Our findings at the firm- and research program levels also suggest that firms use terminations as part of their innovation strategy. We observe that firms with larger patent portfolios and more alliance activity engage in higher rates of termination. This suggests that the search and termination activities may be related, and firms may follow different strategies in how they couple these competencies.

The main finding of our study is that the structure of knowledge within a firm's research portfolio influences termination decisions. Prior research has highlighted the relationship between interdependencies and adaptation through simulations (Levinthal, 1997; Rivkin, 2000). Accordingly, interdependencies and complexity raise the difficulty of adapting to changing conditions. In more formal terms, Levinthal (1997) shows that interdependencies increase the ruggedness of the landscape such that incremental adaptive moves could hurt the overall fitness of a firm rather than increase it. In other words, interdependencies may reduce a firm's ability to adapt to change. Few empirical studies, however, empirically test this relationship. Our study provides an empirical test based on an intermediate outcome, termination. Termination is an important tool for adaptation, as it allows firms to redirect search efforts based on newly acquired information. As recent research suggests, adaptation is in large part made possible by redeployment of a firm's resources released after reconfiguration (Capron, Mitchell, and Swaminathan, 2001; Helfat and Winter, 2011; Teece, 2007). If, however, firms have difficulty terminating underperforming inventive paths due to the complexity introduced by interdependencies, adaptation could be hindered.

By building on the literature on heuristics in search, we put forth the argument that boundedly rational managers may employ heuristics in choosing which inventions to terminate, especially when knowledge interdependencies are high. The results suggest that interdependencies across research programs and the level of external competition can both act as termination heuristics. Our study and findings reveal an interesting asymmetry between initial search and later termination: While prior research suggests that firms may err toward search that is local and path dependent (e.g., Ahuja and Lampert, 2001), our results highlight that, once a search effort that is boundary spanning or new to the world is initiated, managers exhibit a preference to continue rather than terminate it, especially under high complexity.

The research presented here builds upon our understanding of R&D portfolio management by stressing the importance of interdependencies in evaluations of R&D investments. As we discussed at the beginning of the paper, the methods of R&D portfolio evaluations have largely ignored interdependencies between inventions (Brunner *et al.*, 2008). The portfolio decisions in real life are, however, complex and multifaceted. Ignoring interdependencies could lead to erroneous evaluations, and limit the value of R&D evaluation methods in practice. Our research shows that interdependencies are an important factor influencing portfolio management, and should be incorporated into models of R&D evaluation.

Finally, the present study also makes an empirical contribution by examining patent terminations from a knowledge perspective. While the patent production functions have been studied extensively in the literature (Griliches, 1979; Kortum and Lerner, 2000; Lanjouw and Schankerman, 2004), patent terminations have received less attention. To our knowledge, our study is one of the first to examine heterogeneity in terminations as a function of interdependencies within a patent portfolio.

This study can be extended in several ways. First, we rely on patent data to capture the inventive effort within pharmaceutical firms. Even though firms in the pharmaceutical industry patent most of their ideas (Cohen *et al.*, 2000; Levin *et al.*, 1987), we could still be missing ideas that were eliminated before the patenting stage. Future studies could aim to capture a more comprehensive population of all ideas and their progression in the development cycle. In addition, identifying projects with multiple patents could be beneficial. Even though we believe this omission provides a more conservative test of our hypotheses (interdependent patents, if they belong to the same project, would be terminated together, causing a positive correlation between interdependence and likelihood of termination), a new study with this control would be helpful. Third, even though we have presented theory and results consistent with the mechanism of cognitive limitations and decision heuristics, we have no direct way of observing actual decisions. Our approach to heuristics is consistent with a stream that views them as helpful and simplified decision rules (Bingham and Eisenhardt, 2011; Nelson and Winter, 1977; Newell and Simon, 1972), and our results do not preclude the possibility that the resulting decisions may be the optimal ones in a given situation. Future work that can provide in-depth observations of termination decisions in the field could enrich these initial findings. Fourth, although there are some advantages to limiting the scope of current study to the pharmaceutical industry, the findings may not generalize across other industries. Last, the current study does not discuss the performance implications of changes in decision making as a result of interdependencies. Future work that can link the variation in terminations as a result of interdependencies and firms' innovation performance can further our understanding of innovation process.

To conclude, our research underlines the importance of termination as an adaptive tool. Given the high rates of termination observed in the pharmaceutical industry, we find that firms use terminations strategically to shape portfolios of inventive effort. We submit that managers should approach termination decisions proactively, as they are both prevalent and important. Researchers and managers should not underestimate the importance of interdependencies in portfolio evaluations. Our study suggests that interdependencies in research portfolios may influence not only the effectiveness of search, but also firms' selection strategies.

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APPENDIX 1

A patent granted by the USPTO has a 20-year term from filing. The assignee must, however, pay a maintenance fee to renew the patent at four, eight and 12 years. A failure to do so results in termination of the patent protection. Maintenance fees are modest: In 2018, the 4-, 8-, and 12-year renewal fees are $1,600, $3,600, and $7,400, respectively. When a firm does not renew a patent, it is plausible to infer that the expected value of the patent for the firm is below these rates (e.g., Lanjouw, 1998; Pakes, 1986; Schankerman and Pakes, 1986). Considering that a firm can extract value from a patent in a multitude of ways, including commercialization, legal action, transfer or licensing (e.g., Levitas and Chi, 2010; Reitzig, 2004; Somaya, 2012), termination of a patent is a good indicator of the patent's (lack of) value to the firm. Indeed, patent renewals are associated with indicators of expected value, such as the number of forward citations (Harhoff *et al.*, 1999; Lanjouw and Schankerman, 2004; Moore, 2005; Serrano, 2010).

Moore (2005) suggests that the rates of termination underline the role of renewal fees as an innovation sorting mechanism. Average patent renewal rates are below 50 percent (Lanjouw, 1998; Pakes, 1986; Schankerman, 1998), but vary by technology and country (Schankerman, 1998; Scotchmer, 1999). For instance, the rates of termination are higher in biotechnology and pharmaceuticals than in computer hardware and software (Moore, 2005). Biotechnology and pharmaceutical companies patent even the smallest ideas earlier in the development process, relying on sorting at later stages, whereas computer companies patent tangible products and technologies (Lehman, 2003; Moore, 2005).

Examination of patent terminations in strategy is relatively recent. Scholars find that terminations are related to the type of research and characteristics of the inventors (Liu, 2014; Liu *et al.*, 2008; Lowe and Veloso, 2015). Examining how firms learn from terminations, Khanna *et al.* (2016) found a link between terminations and subsequent R&D performance.

TABLES AND FIGURES

Table 1. Research Programs: IMS Health's Uniform System of Classification (USC)

2 Analgesics	24 Genitourinary	38 Anti-Fungal Agents	67 Sedatives
9 Antiarthritics	28 Respiratory Therapy	39 Diabetes Therapy	69 Smoking Deterrents
11 Hemostatic Modifiers	29 Cardiac Agents	41 Diuretics	74 Tuberculosis Therapy
14 Antihistamines, Systemic	30 Antineoplastic Agents	48 Blood Growth Factors	78 Miscellaneous Preps
15 Anti-Infectives, Systemic	31 Vascular Agents	52 Hormones	82 Antiviral
17 Antinauseants	32 Antihyperlipidemic Agents	59 Musculoskeletal	85 Sexual Function Disorders
18 Anti-Obesity	33 Contraceptives	60 Nutrients & Supplements	86 Immunologic Agents
20 Neurological Disorders	34 Cough/Cold Preparations	61 Ophthalmic Preparations	
23 Gastrointestinal	37 Dermatologicals	64 Psychotherapeutics	

Table 2. Descriptive Statistics and Partial Correlations

Variables	Mean	SD	Min	Max	1	2	3	4	5	6	7	8	9	10	11
1. Patent termination	0.192	0.394	0	1	1										
2. Interdependence within research program	0.016	0.039	0	0.45	-0.05	1									
3. Interdependence across research program	0.014	0.011	0	1	-0.02	-0.01	1								
4. Extent of competition	25.80	42.27	0	347	-0.01	0.09	0.02	1							
5. Patents in research program	13.54	13.36	4	80	-0.01	0.09	0.03	0.24	1						
6. Number of citations	5.604	7.331	0	156	-0.03	0.05	0.09	-0.04	0.05	1					
7. Number of claims	11.66	3.718	1	96	0.05	0.16	0.03	0.05	0.16	0.07	1				
8. Technological diversity	0.106	0.311	0.01	3.469	-0.02	0.10	0.03	-0.02	0.04	0.01	0.10	1			
9. Number of countries	1.347	1.049	1	7	0.01	-0.02	0.02	0.01	-0.02	0.01	0.08	0.14	1		
10. Productivity	458.1	493.3	1	2,311	0.08	-0.15	-0.06	0.08	-0.15	0.03	0.41	0.07	0.26	1	
11. Number of alliances	1.598	1.634	0	17	0.02	0.48	-0.03	0.02	0.48	0.02	0.61	0.13	0.01	0.11	1

Table 3. Fixed-effects Logistic Model Estimates for Patent Termination (DV = Likelihood of Patent Termination)

Variable	**1**		**2**		**3**		**4**		**5**	
Interdependence within research program			-3.16	***0.010***	-0.55	***0.406***	-4.40	***0.002***	-1.16	***0.314***
			(1.34)		(2.32)		(1.51)		(2.38)	
Interdependence within research program X Interdependence across research programs					-201.03	***0.090***			-265.36	***0.047***
					(152.50)				(158.70)	
Interdependence within research program X Extent of competition							0.39	***0.014***	0.47	***0.006***
							(0.36)		(0.20)	
Interdependence across research programs	-3.23	***0.319***	-3.42	***0.291***	-1.53	***0.661***	-3.49	***0.281***	-3.42	***0.759***
	(3.24)		(3.24)		(3.51)		(3.24)		(3.24)	
Extent of competition	-0.00	***0.479***	-0.01	***0.463***	-0.01	***0.476***	-0.01	***0.165***	-0.01	***0.138***
	(0.00)		(0.01)		(0.01)		(0.01)		(0.01)	
Patents in research program	0.00	***0.903***	0.00	***0.943***	0.00	***0.938***	0.00	***0.976***	0.00	***0.969***
	0.00		(0.00)		(0.00)		(0.00)		(0.00)	
Number of citations	-0.01	***0.170***	-0.01	***0.170***	-0.01	***0.170***	-0.01	***0.177***	-0.01	***0.178***
	(0.01)		(0.01)		(0.01)		(0.01)		(0.01)	
Number of claims	0.05	***0.005***	0.05	***0.004***	0.04	***0.004***	0.05	***0.002***	0.05	***0.002***
	(0.01)		(0.01)		(0.01)		(0.01)		(0.01)	
Technological diversity	0.16	***0.283***	0.16	***0.267***	0.16	***0.272***	0.16	***0.264***	0.16	***0.271***
	(0.14)		(0.15)		(0.15)		(0.15)		(0.15)	
Number of countries	-0.01	***0.667***	-0.01	***0.694***	-0.01	***0.714***	-0.01	***0.741***	-0.01	***0.774***
	(0.03)		(0.04)		(0.03)		(0.03)		(0.04)	
Productivity	0.00	***0.007***	0.00	***0.011***	0.00	***0.011***	0.00	***0.009***	0.00	***0.010***
	(0.00)		(0.00)		(0.00)		(0.00)		(0.00)	
Number of alliances	-0.03	***0.356***	-0.00	***0.996***	-0.00	***0.968***	-0.00	***0.910***	-0.00	***0.951***
	(0.03)		(0.03)		(0.03)		(0.03)		(0.03)	
Year dummies	*YES*		*YES*		*YES*		*YES*		*YES*	
Wald χ^2	*92.60*		*98.60*		*100.41*		*102.49*		*105.44*	
χ_p^2	*0.00*		*0.00*		*0.00*		*0.00*		*0.00*	
# Observations	*7124*		*7124*		*7124*		*7124*		*7124*	
# Groups	*85*		*85*		*85*		*85*		*85*	

Numbers in the parentheses are standard errors for respective coefficients and numbers in bold are the *p-values*. The *p-values* for hypothesis tests are one-tailed.

Table 4. Robustness tests – fixed effects logistic models (DV = Likelihood of Patent Termination)

Variable	**1**		**2**		**3**		**4**	
Interdependence within research program	-3.500	***0.023***	-0.31	***0.450***	-3.16	***0.010***	-0.86	***0.357***
	(1.76)		(2.52)		(1.34)		(2.36)	
Interdependence within research program X Interdependence across research programs			-255.98	***0.049***			-277.79	***0.041***
			(154.66)				(160.1)	
Interdependence within research program X Extent of competition			0.66	***0.008***			4.96	***0.007***
			(0.26)				(2.16)	
Interdependence within research program X Patents in research program	0.02	***0.378***	-0.08	***0.164***				
	(0.03)		(0.08)					
Interdependence across research programs	-3.42	***0.291***	-1.16	***0.740***	-3.42	***0.291***	-0.98	***0.779***
	(3.24)		(3.50)		(3.24)		(3.51)	
Extent of competition	-0.00	***0.455***	-0.01	***0.094***	-0.15	***0.257***	-0.25	***0.075***
	(0.00)		(0.01)		(0.13)		(0.14)	
Patents in research program	-0.00	***0.973***	0.00	***0.748***	0.00	***0.882***	0.00	***0.967***
	0.00		(0.00)		0.00		0.00	
Number of citations	-0.01	***0.172***	-0.01	***0.178***	-0.01	***0.163***	-0.01	***0.171***
	(0.01)		(0.01)		(0.01)		(0.01)	
Number of claims	0.05	***0.004***	0.05	***0.003***	0.04	***0.004***	0.05	***0.002***
	(0.01)		(0.01)		(0.02)		(0.01)	
Technological diversity	0.16	***0.266***	0.16	***0.276***	0.16	***0.278***	0.15	***0.287***
	(0.14)		(0.15)		(0.15)		(0.15)	
Number of countries	-0.01	***0.695***	-0.01	***0.788***	-0.01	***0.708***	-0.01	***0.802***
	(0.03)		(0.03)		(0.04)		(0.03)	
Productivity	0.00	***0.011***	0.00	***0.009***	0.00	***0.008***	0.00	***0.007***
	(0.00)		(0.00)		(0.00)		(0.00)	
Number of alliances	-0.03	***0.985***	-0.01	***0.959***	-0.00	***0.988***	-0.00	***0.952***
	(0.03)		(0.03)		(0.03)		(0.03)	
Year dummies	*YES*		*YES*		*YES*		*YES*	
Wald χ^2	*98.69*		*106.45*		*99.37*		*106.01*	
χ_p^2	*0.00*		*0.00*		*0.00*		*0.00*	
# Observations	*7124*		*7124*		*7124*		*7124*	
# Groups	*85*		*85*		*85*		*85*	

Numbers in the parentheses are standard errors for respective coefficients and numbers in bold are the *p-values*. The *p-values* for hypothesis tests are one-tailed.

Table 5. Fixed-effects Negative Binomial Model Estimates for Intensity of Patent Termination

Variable	1		2		3		4	
Interdependence within research program	-2.57	***0.000***	-2.60	***0.000***	-6.07	***0.000***	-7.01	***0.000***
	(0.26)		(0.26)		(1.40)		(1.51)	
Interdependence within research program X Interdependence across research programs			-6.46	***0.058***			-23.14	***0.053***
			(4.10)				(14.34)	
Interdependence within research program X Extent of competition			0.02	***0.000***			0.03	***0.018***
			(0.00)				(0.02)	
Interdependence across research programs	-5.72	***0.000***	-6.00	***0.005***	-4.15	***0.000***	-5.01	***0.001***
	(0.25)		(0.52)		(1.48)		(1.51)	
Extent of competition	0.01	***0.000***	0.01	***0.000***	0.04	***0.000***	0.04	***0.002***
	(0.00)		(0.00)		(0.01)		(0.01)	
Patents in research program	0.00	***0.516***	0.00	***0.898***	0.00	***0.898***	0.00	***0.921***
	0.00		0.00		0.00		0.00	
Number of citations	-0.00	***0.037***	-0.00	***0.991***	-0.00	***0.986***	-0.00	***0.879***
	(0.01)		(0.01)		(0.01)		(0.01)	
Number of claims	0.00	***0.186***	0.00	***1.00***	0.00	***0.998***	0.00	***0.951***
	(0.00)		(0.00)		(0.00)		(0.00)	
Technological diversity	0.03	***0.184***	0.03	***0.350***	-0.09	***0.354***	-0.10	***0.305***
	(0.02)		(0.02)		(0.10)		(0.10)	
Number of countries	-0.15	***0.116***	-0.16	***0.341***	-0.34	***0.340***	-0.42	***0.240***
	(0.09)		(0.10)		(0.36)		(0.36)	
Productivity	0.00	***0.000***	0.00	***0.032***	0.00	***0.031***	0.00	***0.026***
	(0.00)		(0.00)		(0.00)		(0.00)	
Number of alliances	0.24	***0.000***	0.24	***0.004***	0.17	***0.004***	0.22	***0.000***
	(0.03)		(0.02)		(0.06)		(0.06)	
Constant	0.64	***0.000***	0.65	***0.349***	0.37	***0.356***	0.34	***0.388***
	(0.11)		(0.11)		(0.40)		(0.40)	
Firm fixed effects	*YES*		*YES*		*YES*		*YES*	
Year dummies	*YES*		*YES*		*YES*		*YES*	
Wald χ^2	*2365*		*2388*		*233*		*242*	
χ_p^2	*0.00*		*0.00*		*0.00*		*0.00*	
# Observations	*14821*		*14821*		*821*		*821*	
# Groups	*1462*		*1462*		*85*		*85*	

Models 1, 2: Dependent variable is the number of patents abandoned in a research program.
Models 3, 4: Dependent variable is the number of patents abandoned by the firm.
Numbers in the parentheses are standard errors for respective coefficients and numbers in bold are the *p-values*. The *p-values* for hypothesis tests are one-tailed.

Figure 1. Relationship Between Predicted Probability of Termination of a Patent and Its Interdependence Within the Research Program at Different Levels of Interdependence Across Research Programs

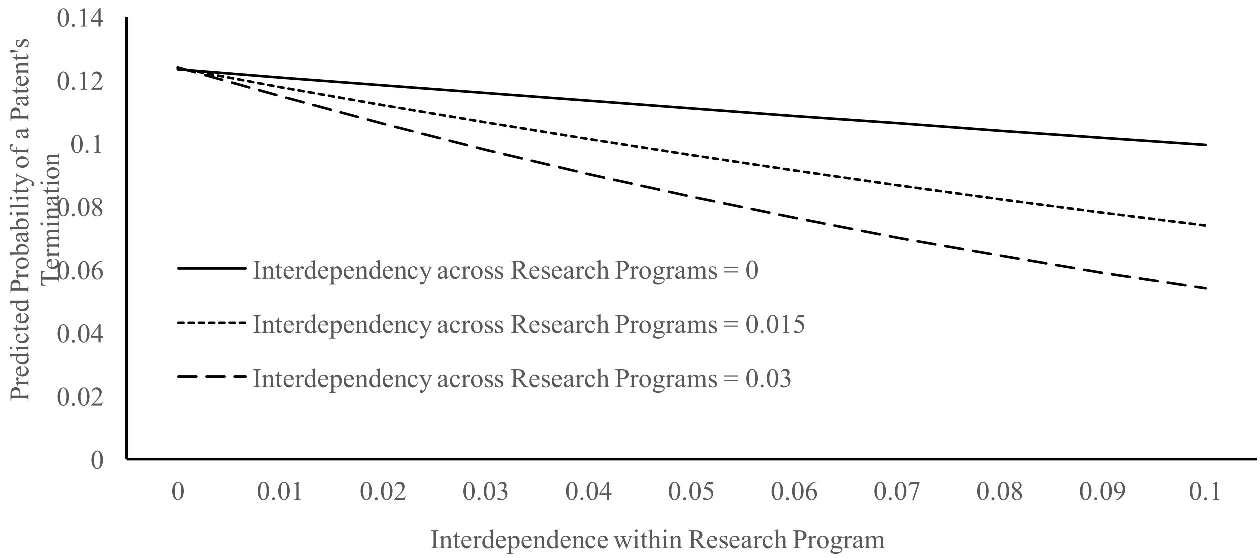

Figure 2. Relationship Between Predicted Probability of Termination of a Patent and Its Interdependence Within the Research Program at Different Levels of Extent of Competition