

A COMPETITION-BASED EXPLANATION OF COLLABORATIVE INVENTION WITHIN THE FIRM

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Existing literature shows that collaborative invention within the firm enhances innovativeness by facilitating knowledge recombination. Despite such benefit, firms vary in their use of collaborative invention when drawing on their individual inventors' knowledge. In addressing this puzzle, we argue that competition from rival products building on similar knowledge compels firms to favor search depth over exploratory search and respond expeditiously, thus reducing a firm's inclination toward collaborative invention. In contrast with prior research's focus on how upstream resources influence a firm's position in downstream markets, this study shows that downstream competition drives heterogeneity across firms in their utilization of upstream resources. Copyright © 2013 John Wiley & Sons, Ltd.

INTRODUCTION

Collaboration has become increasingly prominent in the organization of knowledge-based activities (Wuchty, Jones, and Uzzi, 2007). Collaboration between inventors allows a firm to recombine knowledge residing across these inventors (Almeida and Kogut, 1999; Corredoira and Rosenkopf, 2010; Fleming and Sorenson, 2004). It expands a firm's combinatorial opportunities and enhances the potential for breakthrough inventions (Fleming, Mingo, and Chen, 2007; Rosenkopf and Almeida, 2003). Collaborative invention thus constitutes a useful way for a firm to utilize its inventors' knowledge and create a competitive advantage (Felin and Hesterly, 2007; Grant, 1996; Liebeskind, 1996). However, despite these

known benefits of collaborative invention, the literature has stopped short of explaining why its incidence varies across firms. This leaves an unanswered question—why are some firms more inclined toward collaborative invention while other firms have more of their inventors inventing individually?

To address this question, a helpful start is to note that collaborative invention likely involves a different type of search (Dosi, 1982; Katila and Ahuja, 2002) than inventing with individual inventors. It also entails more communication and coordination difficulties between individuals (Becker and Murphy, 1992; Kretschmer and Puranam, 2008). Consequently, collaborative invention may not always be the most appropriate way for a firm to expend its R&D efforts and coordinate its inventors. It is a strategic choice rather than a superior practice that firms will uniformly adopt. Accordingly, a theory of collaborative invention can be one that identifies situations requiring the type of search that collaboration involves, or justifying the difficulties that collaboration entails.

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In this paper, we take an initial step toward establishing such a theory by examining the competitive environment as a driver of a firm's collaborative invention. Competition has pervasive effects on a firm's inventive process. Competitive threats can arise from rivals' products, production capacity, market power, or intellectual property (IP) rights (Demsetz, 1973; Dixit, 1980; Gilbert and Newbery, 1982). They influence how much inventive effort a firm invests in particular markets, as evidenced by the extensive studies on R&D races (Doraszelski, 2003; Lerner, 1995; Reinganum, 1985). Competition also influences which technological space a firm explores (Clarkson and Toh, 2010) and what products a firm invests in (Martin and Mitchell, 1998). What is less known thus far is how, for a given amount of inventive effort within a particular technological space, competition also affects the way a firm organizes its inventors, specifically, the extent to which it engages in collaborative invention.

Competition in a product market comes in two forms: products building on similar knowledge and products building on alternative knowledge bases (Dosi, 1982; Nelson and Winter, 1982; Polidoro and Toh, 2011). Prior research focusing on the former has shown that it induces a firm to defend its market position by refining existing products (Anderson and Tushman, 1990; Martin and Mitchell, 1998). We extend this line of research by examining how such form of competition, with its inherent cumulative improvements in product features (Green and Scotchmer, 1995; Murray and O'Mahoney, 2007), induces a firm to organize its inventors for greater search depth with less collaborative invention, rather than for greater exploratory search via more collaborative invention. In addition, as such competition increases, a firm likely has less slack time to deal with collaboration difficulties, and having inventors work individually instead may be preferable. Accordingly, we propose that as a firm faces greater competition from rival products building on similar knowledge, it engages in less collaborative invention for a given level of inventive effort.¹

Further, we examine a firm's commercial and technical abilities as boundary conditions for this main proposition, which help explain why firms differ in their use of collaborative invention even when they face the same level of competition.

To test our propositions, we focus on pharmaceutical firms producing antihypertensives (drugs that lower blood pressure) from 1980 to 2004. Three features of this setting are particularly relevant to our empirical tests. First, by tracing the pharmacological mechanism underlying a firm's antihypertensive, we can ascertain the knowledge underlying that drug (Reuben and Wittcoff, 1989) and precisely identify rival drugs building on similar knowledge. This fine-grained measure of competition enables a sharper test of our propositions, by identifying competition from only rival products (antihypertensives) building on similar knowledge (mechanism) as a firm's product, rather than including all competing products in the market. Second, by identifying specific patents protecting antihypertensives, we can map rival products building on a particular knowledge to the relevant subset of a firm's subsequent inventive activities involving such knowledge. Third, by exploiting a flux period in the mideighties induced by mergers and acquisitions within the pharmaceutical industry, we can instrument the variable capturing competition from similar antihypertensives. Such instrumental variable approach helps address potential endogeneity issues, specifically, that firms engaging in collaborative invention may tend to operate in areas with less competition, or that the nature of a certain technological area may draw more competition and concurrently require greater depth in search through individual inventors. We elaborate on the merits of these features in a later section.

Through our propositions, we introduce a competition-based explanation for why, despite the well-established benefits of combining knowledge across individuals, firms vary in their use of collaborative invention. In the innovation process, whether a firm utilizes its individual inventors more as a set of collaborative inventors or more as a collection of solo inventors depends on the competition it faces. This paper, by highlighting such role of competition in firms' resource utilization, advances theory on the sources of competitive

¹ We do not expect our propositions to generalize to competition from products building on alternative knowledge bases because, as prior studies have shown, this form of competition exerts conflicting influences, sometimes compelling a firm to refine its own technology (Anderson and Tushman, 1990: 611), while at other times inducing a firm to branch away from its technology

and explore alternatives instead (Martin and Mitchell, 1998: 756).

advantage. A common theme in strategy research is that firms perform differently because they possess heterogeneous resources (Barney, 1991; Wernerfelt, 1984), and resource heterogeneity, in turn, arises when firms accumulate resources in dissimilar ways (Ahuja and Katila, 2004; Helfat, 1997). This paper, in contrast, focuses more on firms' resource utilization rather than accumulation, and shows that, even for an activity such as collaborative invention that seems purely upstream and unrelated to downstream markets, product competition in fact still plays a crucial role. Simply put, although firms' upstream resources shape their downstream performances, in some circumstances it is precisely downstream competition that drives the way firms utilize their upstream resources. In the final section, we elaborate on these theoretical implications.

THEORY AND HYPOTHESES

Collaborative invention allows a firm to draw on a greater number and diversity of knowledge components from its inventors, creating greater recombinant potential (Fleming, 2001). Moreover, collaborative invention entails social interactions that enhance creativity and enable inventors to combine previously unconnected ideas, technologies, and processes (Fleming *et al.*, 2007), which in turn increases the incidence of impactful, breakthrough innovations (Singh and Fleming, 2010). Although collaborative invention provides these benefits, its practice is not uniform across firms. Some firms tend to have more collaboration between inventors, whereas others are more inclined to let their inventors work individually (Dahlin, Taylor, and Fichman, 2004; Singh and Fleming, 2010). To explain this divergent choice, we first highlight two attributes of collaborative invention—the type of search it facilitates and the difficulties it entails. We then examine how competition from rival products building on similar knowledge diminishes a firm's inclination to engage in collaborative invention.

Collaborative invention: type of search and collaboration difficulties

Collaborative invention is conducive to distant and exploratory search (Levinthal, 1997; March, 1991), as pooling multiple individuals' knowledge expands the combinatorial space (Singh and

Fleming, 2010). When multiple inventors come together with different knowledge, as long as a criterion is to include knowledge components from each inventor, the resultant combination will on average incorporate more distant components and accordingly be more radical. In contrast, when an inventor operates individually, search tends to occur in a narrower space and often with greater depth as the inventor engages in more use and reuse of her existing knowledge (Katila and Ahuja, 2002). This deepens individual inventors' understanding of concepts and scientific principles underlying their inventions, and reduces potential errors, leading to more reliable and predictable search (Eisenhardt and Tabrizi, 1995). The inventive outcomes are consequently more incremental and cumulative over prior inventions (Tushman and Anderson, 1986). Hence, firms tend to choose collaborative invention when they wish to engage in exploratory search and, conversely, tend to have its inventors inventing individually in situations requiring search depth. Indeed, firms often reallocate inventors, for instance, from more exploratory projects to ones more focused on the inventors' specialized expertise, so as to increase their efficiency in product innovation activities (Edmondson and Nembhard, 2009).

The second attribute of collaborative invention concerns the difficulties it entails. Collaboration requires coordination, which can be problematic when collaborating individuals are specialists in different fields (Becker and Murphy, 1992; Kretschmer and Puranam, 2008). It also requires individuals to synchronize objectives, agree on the sequence of activities, and plan for connecting interfaces between different parts of projects (Lawrence and Lorsch, 1967; Sanchez and Mahoney, 1996). Moreover, when inventors collaborate, a firm cannot easily monitor each individual's inputs to the joint production of knowledge, or even identify what each individual can potentially contribute (Eisenberg, 2001). When individuals anticipate such problems of imperfect attribution in jointly obtained outcomes, their incentives to contribute optimal effort toward the joint activity in the first place further reduces (Aghion and Tirole, 1994), which can render a firm vulnerable to shirking, free-riding, and output expropriation by opportunistic individuals (Pisano, 1990; Williamson, 1975). Additional obstacles can arise from the interpersonal context surrounding collaboration. The very diversity of knowledge

and perspectives within teams that spurs innovations can also give way to disagreements about delegation of duties and resources, which eventually prevent the team from realizing those potential benefits (Jehn, Northcraft, and Neale, 1999). Although these collaboration difficulties are not insuperable, reducing frictions in coordination, designing suitable reward structures, and mitigating interpersonal conflicts take effort and time. Thus, when deciding whether or not to engage in collaborative invention, a firm likely assesses whether the situation calls for a greater need of exploratory search through collaborative invention so as to justify the effort and time required to mitigate the associated collaboration difficulties.

Effect of competition from similar products on collaborative invention

Having highlighted the type of search that collaborative invention facilitates and the difficulties it entails, we now explain how competition from products building on similar knowledge, by shaping the salience of these two attributes, affects a firm's collaborative invention. Competition from products building on similar knowledge creates pressure for a firm to deal with rivals' incremental product improvements (Green and Scotchmer, 1995). These rival products often do not encompass major changes in such knowledge. They constitute minor improvements upon product features relevant to users. For example, in the cell phone industry, competing smart phones build on existing platforms with minor improvements in physical features and usability. Similarly, rivalry in the pharmaceutical industry often arises from competing versions of similar drugs improving on some dimensions of efficacy or safety (Danzon, 2000). For instance, different angiotensin-converting enzyme inhibitors, such as Parke-Davis's quinapril (Accupril) and Ciba-Geigy's benazepril (Lotensin), achieve a similar effect in the treatment of hypertension (Scriabine, 1999: 188). Rival products building on similar knowledge may also compete for new applications through incremental modifications. For example, with small tweaks to polytetrafluoroethylene (also known as Teflon), the technology's application shifted from nonstick materials in cooking pans to slide-inducing materials in gears, bearings, uranium-holding pipes, and roof coatings. Likewise, firms have used antihypertensives building

on the beta-blockers mechanism to treat arrhythmia (Scriabine, 1999).

Such competition exists even in the presence of patent protection. The economics literature shows that patent protection does not fully prevent rivals from inventing around and creating imitative products (Dasgupta, 1988: 74; Gilbert and Newbery, 1982: 519). As Mansfield, Schwarz, and Wagner note, "Contrary to popular opinion, patent protection does not make entry impossible, or even unlikely"² Mansfield, Schwarz, and Wagner (1981: 913). Although pharmaceutical firms actively use patents to deter imitation (Cohen, Nelson, and Walsh, 2000), patents do not award exclusionary rights over the scientific principles underlying drugs. A patent protecting a drug does not prevent rivals from drawing on the mechanism of action underlying that drug to create similar "me-too" drugs (Danzon, 2000; Higgins and Rodriguez, 2006). For instance, following the success of chlorothiazide, a diuretic antihypertensive, many firms invented around Merck's patent, resulting in more than twenty related diuretics in the market (Scriabine, 1999: 196).

Competition from rival products building on similar knowledge influences a firm's collaborative invention in two ways. First, it shifts a firm's priority away from exploratory search toward greater search depth. With the threat of losing market share to these rival products, a firm tends to concentrate on improving its existing products via minor variations based on that same knowledge, so as to defend its market position (Anderson and Tushman, 1990; Martin and Mitchell, 1998). For example, increasing competition among calcium channel antagonists in the treatment of hypertension induced firms to focus on minor improvements relative to similar drugs, such as longer duration of action in the case of Pfizer's amlodipine, or availability of a water-soluble derivative for intravenous administration in the case of Syntex's nicardipine (Scriabine, 1999: 193). Also, as rival products cumulatively improve within a domain, the problems they aim to solve become increasingly nuanced and specific to the domain. To create the next technically superior product within the same domain, a firm needs greater domain-specific experience and deeper understanding of

² These authors showed that 60 percent of the patented successful innovations in their sample were imitated within four years of their introduction.

the underlying knowledge. These may come in the form of knowing how to decompose problems, what specific knowledge combinations are meaningful, or where to look for feasible solutions within the domain (Eisenhardt and Tabrizi, 1995; Katila and Ahuja, 2002). As knowledge gains depth, it often becomes more tacit and harder to communicate across individuals. This is akin to the idea that mastery of skills is hard to codify and typically requires prolonged apprenticeships. In these instances, having inventors individually burrowing for greater depth is likely more effective. Moreover, exploratory search inherent in collaborative invention tends to be risky (March, 1991), as it involves experimenting with relatively untested knowledge combinations. Bearing such risk requires a firm to secure at least a minimum base of financial performance in the interim. Competition, by threatening the market share of a firm's products, challenges such base. Thus, in the face of competition, exploratory search through collaborative invention tends not to be a high firm priority.

Second, competition from rival products building on similar knowledge typically requires swift responses, which diminishes the time that a firm can afford to incur for dealing with collaboration difficulties. As such rival products typically target users with similar preferences and introduce refinements over relevant functional dimensions, they could quickly erode a firm's market share (Christensen, 1997; Martin and Mitchell, 1998). Furthermore, a firm's expected returns from investing in a particular underlying knowledge arise from not only its current product building on this knowledge but also the whole stream of potential products in the future exploiting this knowledge. Rival products cumulatively exhaust these future opportunities. To avoid losing current market share and missing future exploitative opportunities, a firm needs to rapidly introduce new products building on its current technology. This time pressure is aggravated by the fact that cumulative rival products, by advancing on various technical dimensions, raise technical hurdles for subsequent products, and a firm needs time to overcome these hurdles. This time urgency induces a firm to direct its inventive effort away from collaborative invention, as collaborative invention requires time for overcoming its inherent difficulties, toward having more inventors working individually instead.

In summary, holding other influences constant, competition from rival products building

on similar knowledge, by shifting a firm's priority away from exploratory search toward greater search depth and by increasing the pressure for a firm to swiftly refine its products, pushes that firm away from collaborative invention toward a greater degree of individual invention.

Hypothesis 1 (H1): The more rival products build on similar knowledge, the less a firm subsequently engages in collaborative invention when using this knowledge.

H1 accounts for firm variation within the same product market at a point in time. Depending on the knowledge they use, firms face different levels of similar product competition and, accordingly, exhibit different propensities toward collaborative invention. However, variation in collaborative invention across firms using the same knowledge and hence facing the same competition remains to be explained. To explain this variation, we examine firm attributes rendering a firm especially susceptible to the main effect in H1. Looking closely at the earlier mechanisms, we identify two such attributes—commercial abilities and technical abilities.

The first contingency is a firm's commercial abilities. Abilities to commercialize inventions reside not only in tangible downstream assets, such as production and distribution systems (Cohen and Klepper, 1996), but also in intangible skills, such as the craft of managing the trial-and-error process in development phases, awareness of appropriate experimental settings for testing prototypes' feasibility, sense of the right market for product launch (Nerkar and Roberts, 2004), and relationships with distribution networks (Mitchell, 1989).

While similar rival products steer a firm toward greater search depth (less collaborative invention) to advance its product's technical attributes, its commercial abilities dampen such effect. With sufficient commercial abilities, a firm can still push its product to commercial success even if it is technically inferior. For example, in the pharmaceutical industry where physicians cannot fully observe the intrinsic quality of drugs (Bodewitz, Buurma, and de Vries, 1987), a firm can rely on its commercial abilities to shape physicians' prescribing behavior (Avorn, Chen, and Hartley, 1982; Azoulay, 2002). A firm with strong commercial abilities is less threatened by similar rival products and better able

to secure a minimum base of financial performance despite rivals' technical advances. This allows a firm to still engage in exploratory search for potential breakthroughs via collaborative invention in spite of competition.

In contrast, a firm with weaker commercial abilities is more susceptible to the pressure of competition. With fewer downstream assets to bolster its product's performance, a commercially weaker firm is more vulnerable to the technical challenges stemming from similar rival products. If this firm decides to remain a competitor in this market, its weaker commercial abilities creates a greater need for it to keep up with technical improvements in its products, so as to avoid losing market share. These incremental improvements can be best achieved via greater search depth (less collaborative invention). This leads to our first contingency effect:

Hypothesis 2 (H2): Rival products building on similar knowledge reduce a firm's subsequent collaborative invention to a greater degree when that firm has lower commercial abilities.

The second contingency is a firm's technical abilities. This refers to a firm's abilities to rapidly create new products based on a particular knowledge. It includes how quickly a firm can figure out which and how knowledge components can be combined (Fleming and Sorenson, 2004). For example, in new drug creations, it refers to how quickly a firm can decipher what combinations of compounds are scientifically sound and will result in feasible drugs, and can know how a core set of drug components can be modified to improve efficacy or safety (Thomke and Kuemmerle, 2002). Related components exhibit varying degrees of interdependence (Thompson, 1967); learning which existing couplings to break and which new ones to establish instead takes time (Yayavaram and Ahuja, 2008). These abilities are sticky and accumulate with time and experience (Nerkar and Roberts, 2004; Szulanski, 1996). When new inventive opportunities arise, for instance, upon scientific discovery of new knowledge, a firm with technical abilities is quicker to capitalize on them through the creation of new technically feasible inventions.

Technical abilities attenuate competition's effect on eroding a firm's time for dealing with collaboration difficulties. With greater technical abilities

giving faster inventive speed, a firm has more time to resolve collaboration difficulties without being too slow to market. Accordingly, such firm has less need to reduce its collaborative invention when similar rival products threaten its market share. Also, it can still afford to use collaborative invention for capturing further inventive opportunities from the same knowledge, despite rivals eroding slack time and jostling to expropriate these opportunities. Moreover, this firm requires less time to overcome technical hurdles raised by rivals' cumulative products, which we described earlier.

Conversely, a technically weaker firm faces more time pressure to overcome the hurdles arising from competing rival products. As we discussed earlier, similar rival products, with improvements along narrow functional dimensions, create pressure on a firm to defend its market position and respond with incremental improvements. For example, when Akrimax's propranolol (a beta-blocker antihypertensive) demonstrated a negative feature of producing vivid dreams in some patients, its rival, Bristol, improved on its beta-blocker nadolol by inhibiting that feature (Scriabine, 1999: 184). Clearly this improvement rendered the rival drug (nadolol) more attractive, especially to patients vulnerable to the side effect of the firm's drug (propranolol). Indeed, nadolol became one of the elite 100 best-selling drugs in the early 1980s according to the *Pharmacy Times*. For a firm that decides to continue competing in the beta-blocker market, the immediate pressure is not about exploring new combinations based on beta-blocker knowledge. Rather, the immediate pressure that such firm faces is to swiftly mitigate its drug's side effect to avoid losing market share. This time pressure is more acute when a firm lacks technical abilities and cannot count on its inventive speed to quickly counter the side effects. Hence, a technically weaker firm has even less time to deal with collaboration difficulties, and would tend to have more inventors individually addressing the cumulative technical challenges instead.³

³ We stress again that the issue here is not whether a technically weak firm will exit the area, or reduce investments in this area and explore some other new areas instead. Rather, it is about whether a technically weak firm chooses collaborative invention, within its given amount of inventive effort, to deal with incremental challenges brought on by competition. Moreover, in the context of antihypertensives, firms are unlikely to simply give up the market in the face of competition from similar drugs, since antihypertensives are typically commercially successful

In sum, competition's effect of reducing collaborative invention is more pronounced when a firm has lower technical abilities. This leads to our second contingency effect.

Hypothesis 3 (H3): Rival products building on similar knowledge reduce a firm's subsequent collaborative invention to a greater degree when that firm has lower technical abilities.

METHODS

We test our propositions in the setting of firms producing antihypertensives in the United States from 1980 to 2004. Collaborative invention is salient in this setting, as firms' knowledge of chemical compounds and experience in recombining them are crucial in creating feasible drugs (Henderson and Cockburn, 1994; Thomke and Kuemmerle, 2002). Moreover, commercial and technical abilities are relevant firm attributes in this setting. Firms need to demonstrate their drugs' merits to the U.S. Food and Drug Administration (FDA), which reviews new drugs before market launch, and to physicians, who prescribe drugs (Polidoro and Theeke, 2012; Schweitzer, 1997). Also, given the complex technical hurdles involved in creating efficacious and safe drugs, firms' technical abilities are clearly critical.

Importantly, in this setting we are able to identify rival products building on knowledge similar to that underlying a firm's product. Antihypertensives lower blood pressure through different mechanisms of action.⁴ These mechanisms capture the key knowledge on human physiology and pharmacology that drugs build on to achieve the intended therapeutic effect (Reuben and Wittcoff, 1989). For instance, angiotensin receptor blockers relax blood vessels, whereas beta-blockers obstruct receptors that otherwise stimulate cardiac output. Table 1 illustrates mechanisms underlying antihypertensives. By tracing the mechanisms underlying antihypertensives, we can go beyond broadly

drugs. Indeed, the *Pharmacy Times* listed 44 antihypertensive drugs among the 200 best-selling drugs in the United States in 1999.

⁴ The therapeutic class of antihypertensives contains both long-standing mechanisms, such as diuretics, and mechanisms introduced more recently, such as angiotensin receptor blockers. Moreover, this class accounts for a significant number of drugs—70 distinct antihypertensives were launched by 2004.

observing rival products with comparable functionalities, to narrowly identify those that build on similar knowledge. This fine-tuned identification facilitates a sharper test, as the arguments behind our propositions involve not just any product market competition, but rather the type of competition that exhausts combinatorial opportunities for particular knowledge. Despite pharmaceutical firms' high patenting propensities (Cohen *et al.*, 2000), patent protection does not fully prevent rivals from creating similar drugs (Danzon, 2000; Higgins and Rodriguez, 2006). Examples of imitative drugs among antihypertensives include "chlorothiazide (Diuril), the first antihypertensive diuretic (1958), with 15 imitations; propranolol (Inderal), the first antihypertensives β -blocker (1964), with 24 imitations" (Achilladelis, 1999: 3). The success of the beta-blocker propranolol "led almost every large pharmaceutical company to mount an intensive search" for similar drugs (Scriabine, 1999: 183). Likewise, the "success of the first three calcium channel antagonists—verapamil, nifedipine, and diltiazem—led almost every major pharmaceutical company to initiate research projects in this area" (Scriabine, 1999: 193).

Further, this setting allows us to map the implemented form of an innovation in the product market (drug) to the inventive activities in R&D that generated the innovation (patents). Following the 1984 Hatch-Waxman Act, the FDA started to compile information about patents protecting pharmaceutical drugs, which enables this mapping. This enables us to go beyond studying collaborative invention between scientists as reflected in patents (Fleming *et al.*, 2007; Singh and Fleming, 2010) to examine how competing drugs affect such collaborative invention. Further, it enables us to narrow down from a firm's collaborative invention in all of its inventive activities to that in the relevant subset involving a particular knowledge underlying drugs. This in turn allows a sharper identification of the effect of competition we propose.

Data

The FDA was the source of data on antihypertensives. For each drug, we collected data on the active ingredient, the innovating firm, its review status,⁵ and approval date. We also gathered data

⁵ The FDA assigns priority review status to drugs that represent promising therapeutic advance.

Table 1. Examples of mechanisms of action among antihypertensive drugs

Mechanism of action	Examples of drugs building on mechanism
Alpha blockers—reduce blood pressure by blocking receptors that reduce blood vessels diameter and increase resistance to blood flow.	Methyldopa (Merck) Doxazosin (Pfizer)
Angiotensin-converting enzyme (ACE) inhibitors—inhibit the enzyme associated with the system of the body preventing rapid blood pressure loss.	Benazepril (Ciba-Geigy) Quinapril (Parke-Davis)
Angiotensin receptor blockers—block angiotensin receptors, thus preventing the enzyme from contracting blood vessels.	Losartan (Merck) Irbesartan (Sanofi)
Beta-blockers—decrease blood pressure by blocking the receptors that otherwise stimulate cardiac output.	Metoprolol (Novartis) Nadolol (Bristol)
Calcium channel blockers—lower blood pressure by limiting the amount of calcium that enters heart cells that generate signals for heart contractions.	Nifedipine (Pfizer) Nicardipine (Syntex)
Diuretics—lead to an increase in urine production, which results in a decrease of the blood volume.	Amiloride (Merck) Indapamide (Sanofi-aventis)

on antihypertensives approved by the FDA prior to 1980 to construct some measures that we detail later. To do so, we searched for all antihypertensives listed in the pharmacological databases *Micromedex*, *Mosby's Drug Consult*, and *Drug Facts and Comparisons*. We then looked for the respective FDA-approval dates in the FDA's list of *Approved Drug Products with Therapeutic Equivalence Evaluation*, also known as the *Orange Book*. The pharmacological databases also furnished information on the mechanism underlying each drug. We then subjected this identification of mechanisms to validation by an external expert in pharmacology and medicinal chemistry. Further, we used the *Orange Book* to identify the patents protecting the drugs in the sample, capturing the multiple patents that a firm oftentimes uses to protect different components of a drug. We then collected detailed data on these patents, including assigned technology classes, inventors, and their locations, from the Cassis database managed by the U.S. Patent and Trademark Office (USPTO). Further, we used the annual lists of the *Pharmacy Times* to identify best-selling antihypertensives. Finally, to construct a control variable we detail later, we used the *Web of Science* to collect data on scientific publications about the drugs in the study.

To build our sample, we started with all FDA-approved antihypertensives between 1980 and 2004. We traced the associated firms, observed the mechanism underlying each firm's drug, and identified all competing drugs based on the same mechanism in each year. Next, we traced each firm's inventive activities that potentially involved

antihypertensive knowledge, so as to measure a firm's collaborative pattern within these activities. Pharmaceutical firms typically operate in multiple therapeutic classes, some of which may not relate to antihypertensive knowledge. We identified the relevant subset of a firm's inventive activities in three steps. First, we compiled all patents for a firm's antihypertensives. Second, we identified the inventors listed in these patents, by mapping their last names and initials of first names within a firm.⁶ Finally, we compiled all patents filed subsequently by that firm involving those inventors. The resulting subset of patents contains inventions created by a firm's inventors who possess knowledge about that firm's antihypertensives.⁷ The unit of analysis for the eventual panel dataset is the firm-year, and the dataset contains 292 observations in the full sample with 27 firms.

Dependent variable

Collaboration ratio

We use patent coauthorships to measure the extent to which a firm engages in collaborative

⁶ Note that by keeping this mapping within a firm, we minimize errors arising from different inventors across firms having the same last names and initials of first names. To further ensure the accuracy of this mapping, we randomly selected 100 pairs of equivalent last names and initials within firms, and manually checked their full first names and middle names. We found no instances where a pair included different inventors.

⁷ 53.4 percent of patents in this subset refer to subsequent combinations involving firms' antihypertensive knowledge geared toward other therapeutic applications.

invention. We trace, for each year, a firm's patents that include inventors with knowledge on antihypertensives, and count the ones listing more than one inventor. As this count may be confounded with a firm's overall inventive effort, we measure the dependent variable as a ratio of such count to a firm's total patents that include inventors with knowledge on antihypertensives in the year. This variable thus indicates a firm's extent of collaborative invention (with the alternative being individual invention) for a given amount of inventive effort.

Patent coauthorships are appropriate proxies for collaborative invention. The U.S. patent laws require that, when an invention results from contributions of several individuals, the "joint inventors must apply for a patent jointly and each must make the required oath or declaration; neither of them alone, nor less than the entire number, can apply for a patent for an invention invented by them jointly" (USPTO, 2012). Accordingly, firms have strong incentives to match patent coauthorship with the underlying collaboration, so as to minimize risk of subsequent patent invalidation. Indeed, past research has demonstrated through field studies that patent coauthorships reflect intensive collaboration and working relationships between coinventors over nontrivial time periods (Fleming *et al.*, 2007) and has established that they capture collaborative invention (e.g., Cockburn and Henderson, 1998; Singh and Fleming, 2010). We also consulted two patent lawyers with vast experience in patent prosecution and strategic patent portfolio management on the possibility that a firm may strategically list only one inventor when an invention indeed results from a larger collaborative effort. They promptly considered this improbable, stressing that a firm's identification of a patent's coinventors is a legal, not a strategic or political, matter. These justifications notwithstanding, we further conducted a series of tests to examine the appropriateness of patent coauthorships as proxies for collaborative invention, which we explain in a later section.

Another potential issue with patent-based measures is that not all firms' inventions are patented. Firms' motivations and patenting propensities may differ significantly across industries (Cohen *et al.*, 2000), such that the collaboration measure may not encompass all relevant inventive activities within a firm. By restricting our sample to antihypertensives, we minimize this problem,

as patenting propensities are likely stable within a product class (Griliches, 1990). Also, while patents may not be perfect measures of inventive outputs, they are relatively reliable indicators of inventive efforts (Hausman, Hall, and Griliches, 1984). Moreover, our focus is on collaborative tendencies as indicated in patents, rather than counts of patents, and *a priori* it is not clear that collaboration tendencies would systematically differ between patented and nonpatented inventions for a firm in a particular year.

Independent variables

Competition from similar antihypertensives (H1)

To capture rival products building on similar knowledge, we create a variable with the number of rival drugs building on the same mechanism of action underlying a firm's drug available in the antihypertensive market in the year preceding the observation year.⁸ By tracing these commercialized rival drugs rather than measuring rivals' knowledge similarity based on patents (e.g., Ahuja and Katila, 2001; Mowery, Oxley, and Silverman, 1998), this variable captures the actual competitive threats rather than early outcomes of rivals' experimentation with similar knowledge as reflected in patents. This is more appropriate for our purpose since patents may only reflect uncertain signs of potential competition, most of which may not materialize.

Commercial abilities (H2)

When measuring a firm's commercial abilities, we focus on abilities a firm needs to advance new drugs through the commercialization stage. Even after a firm establishes that a new drug is efficacious and safe, it requires commercial abilities to successfully distribute and promote the drug's use (Schweitzer, 1997). Such abilities are not just represented by a firm's physical distributions or marketing assets, but also reside in intangible assets such as relationships and knowledge of dealing with physicians. A comprehensive measure should thus focus less on a drug's invention in early stages and more on its commercial

⁸ In cases where a firm had antihypertensives based on different mechanisms, we compute the average count of rival drugs across these mechanisms. Results are robust when we retain only one mechanism for each firm.

performance, and encompass more than traceable physical inputs. We construct a variable with the number of versions of a firm's antihypertensives that made it into the top 100 drugs generating the most sales in dollars in the U.S. prescription market in the year preceding the observation year. To ensure that the variable does not overstate commercial abilities by including duplicate versions with minimal technical advances, we only consider a firm's distinct molecular entities.

Technical abilities (H3)

A key element in H3 is that for a firm with greater inventive speed, its collaborative invention will be relatively unaffected by competition. This speed is manifested in how quickly a firm, upon the discovery of a new mechanism of action to treat hypertension, can create a new drug based on this mechanism. New mechanisms are discovered either in scientific breakthroughs in research institutions or through a private firm's drug-creation process (Scriabine, 1999). Upon such discovery, rival firms would typically vie to create new drugs based on this mechanism (Danzon, 2000). As explained earlier, this rivalry exists in the presence of patent protection, since mechanisms of action *per se* cannot be patented. A firm with greater inventive speed tends to more quickly figure out which knowledge combinations (to create new drugs) are feasible within this mechanism, and hence be an earlier producer of drugs for this mechanism. Accordingly, to create the measure of technical abilities, we trace the order of a firm's antihypertensive within its respective mechanism; that is, whether its drug was the first, or second, or third (and so on) drug to appear in the market upon the introduction of this mechanism. We then calculate the inverse of this order (i.e., reciprocal, $1/n$), such that higher values of this measure reflect greater technical abilities.⁹

⁹ When computing this measure for a firm that had antihypertensives based on different mechanisms, we used the average value for its drugs across mechanisms. Results are robust when we retain only one mechanism for these firms. Even though this measure is constructed as being relative to rivals, one may argue that it does not reflect the firm's contemporaneous (i.e., specific to a point in time) relative abilities. We separately use an alternative measure of technical abilities calculated as the "firm's total patents relative to the average rival's total patents" in the year. Subsequent findings remain fully robust with this alternative measure.

We acknowledge that our measures of commercial and technical abilities do not directly capture abilities but rather capture the performance outcomes of abilities, despite our attempts to closely connect them to the underpinnings of H2 and H3. Observing a firm's abilities is a challenging task (Henderson and Cockburn, 1994). When examining whether these abilities contribute to firm performance, measuring abilities using performance outcomes clearly entails a problem of tautology (Priem and Butler, 2001). However, this tautology is not salient in our study, since we are not examining whether these abilities contribute to firm performance. In our propositions, we do not presume collaborative invention to imply, or lead to, better firm performance than solo-inventor inventions. In fact, for our purpose, the more closely these measures based on performance outcomes (e.g., inverse order of a firm's drug within the mechanism) correlate with the unobserved latent abilities (e.g., technical abilities), the more accurate these measures will be. Moreover, we are not aware of how a potential gap between a firm's abilities and the respective outcomes would vary systematically with both that firm's collaborative invention (dependent variable) and the competition it faces (independent variable). Hence, we have no reason to suspect that this gap would create a systematic bias in our findings.

Control variables

We control for factors that may correlate with the competition from similar products a firm faces and the extent to which it engages in collaborative invention. To account for the potential influence of competing products building on alternative knowledge bases, we include the number of antihypertensives building on mechanisms different from that of a firm's drug. We control for a firm's inventiveness with the count of a firm's patents involving inventors working on antihypertensives in the year. Firms may file for more patents (with solo inventors) for each given invention when faced with greater competition, so as to strengthen its protection against rivals over a particular technological area. We control for a firm's total number of patents filed in the year (spanning beyond patents protecting antihypertensive drugs), which also helps account for firm size. To address the possibility that competition may induce firms to diversify geographically in search of lower costs,

which in turn may hinder collaboration, we control for a firm's number of distinct geographic locations (states or foreign countries) based on information in patents about where inventors reside. To account for effects associated with technological progression, models include the number of years elapsed since the start of the analysis period.

Further, to address the concern that the dissemination of scientific knowledge may spur incidences of imitative drugs (Danzon, 2000; Scriabine, 1999) and reduce a firm's need to explore via collaborative invention, we add a variable with the number of published scientific papers regarding drugs in the focal mechanism of action in the relevant top journals. We define top journals as those accounting for more than two-thirds of the total impact factor in general and experimental medicine, as well as pharmacology, according to the Institute for Scientific Information.¹⁰ A firm may face increasing competition and become more "desperate" as its patents approach expiration (Higgins and Rodriguez, 2006), turning to solo-inventor research to quickly exploit remaining patent lives. We control for such desperation effect with a count of a firm's antihypertensive-related patents nearing expiration, that is, past 15 years since application.¹¹ More alternative mechanisms of action may mean fewer rivals building on a firm's mechanism and increased risk of obsolescence for a firm's knowledge, which accordingly prompt that firm to engage in collaboration to mitigate such risk. To control for this possibility, we include the number of antihypertensive mechanisms. Rivals in competitive environments frequently engage in litigations, and this may induce a firm to invest in more narrow-scope (solo inventor) patents with tighter legal boundaries. We control for such rivals' litigiousness with a count of litigations filed by a firm's rivals that operate in the same mechanism of action. We also add year dummies to control for

¹⁰ It is possible that availability of scientific knowledge does not facilitate a firm's exploratory search in instances where rivals' patent protection is strong, such that this control variable is unnecessary. Additional models dropping this variable show fully robust results.

¹¹ We use 15 years since application as a proxy for "nearing expiration" to account for the Uruguay Round Agreements Act of 1994, which extended patent lengths from 17 years since grant date to 20 years since application date. To ensure that this control is not affected by how we define patents nearing expiration, we also use an alternative measure of the average age of a firm's antihypertensive-related patents (since application) in a robustness test. Results remain robust with this alternative measure.

temporal heterogeneities. We lag all time-varying independent and control variables by one year.

Empirical model

Arguably, the controls above may not fully eliminate omitted-variable bias, as there may still be unobserved features of a firm's technological area that both draw greater competition and necessitate less collaboration. Moreover, the controls do not fully address the possibility of reverse causality; that is, that by engaging in collaborative invention a firm may venture into new areas where competition from similar drugs is low. Both concerns may result in biased estimates due to nonrandomized assignments of observations to levels of the independent variable of interest (Holland, 1986). To address these concerns, we use the instrumental variable approach in two-stage least squares (2SLS) estimation (Berry and Waldfogel, 2001; Wooldridge, 2002).

To instrument competition from similar drugs in the first stage, we use the period in the mid-1980s when there was a spike in merger and acquisition (M&A) activities in the pharmaceutical industry. Unlike M&As in the mid-1990s, which were largely motivated by firms accessing external technologies and accelerating pipelines of new drugs in the midst of impending patent expiration (Higgins and Rodriguez, 2006), M&As in the mid-1980s mostly followed a rationale of corporate growth via best-selling drugs and further research (Achilladelis, 1999).¹² Acquisitions in the mid-1980s occurred at breakneck speed due to corporate quest for greener pastures, momentum in restructuring programs, reassessments of asset values, and strategies of going private (*Chemical Week*, 1986). During this time, rumors of prospective M&A activities generated huge swings in stock prices (*The New York Times*, 1985), and pharmaceutical firms sought to quickly expand their product lines through M&A activities¹³ and pursued potential acquisitions to make themselves less

¹² This difference in M&A rationale is starkly represented in our sample: over our M&A period (1985–1987), there are no firms in our sample that have antihypertensive-related patents near expiration, specifically, beyond 15 years since application date. Hence, firm desperation due to patent expiration is likely not an influence here.

¹³ For instance, by acquiring Revlon's USV Pharmaceutical and Armour Pharmaceutical operations, Rorer added the antihypertensives Hygroton, Regroton, and Lozol to its product line (*The New York Times*, 1985).

vulnerable to takeovers (*Financial Times*, 1985). This widespread M&A prospect created uncertainty that induced firms to hold back on market launch of new drugs, especially in areas with major therapeutic advances, and to focus instead on minor modifications of their drugs.¹⁴ This M&A-induced slowdown in the launch of major therapeutic advances serves as a useful instrument to estimate differential changes in the levels of competition from similar antihypertensives. We use a dummy variable taking the value of 1 for years 1985–1987 (inclusive), and 0 otherwise, to capture the period of spike in M&A activities.¹⁵ We then use a variable with the number of a firm's antihypertensives that received priority review status from the FDA, to indicate the extent to which the firm was working in areas that constitute potential major breakthroughs or significant advances in hypertensive therapy.¹⁶ Finally, we multiply these two variables, and the resulting interaction term serves to estimate differential changes in competition across firms over the M&A-induced flux period.

In the first stage of the 2SLS estimation, we predict changes in *Competition from similar antihypertensives_{it}* with the instruments and control variables:

$$\begin{aligned} \text{Competition from similar antihypertensives}_{it} = & \beta_0 + \beta_1 \text{ M\&A spike period}_{it} \\ & + \beta_2 \text{ Priority drugs}_{it} + \beta_3 \text{ M\&A spike period}_{it} \times \text{Priority drugs}_{it} + \beta_h \text{ Controls} + \varepsilon_{ijt} \end{aligned} \quad (1)$$

In the second stage, we lag the independent variables and estimate the main model:

$$\begin{aligned} \text{Collaboration ratio}_{it} = & \delta_0 + \delta_1 \text{ predicted (Competition from similar antihypertensives}_{it-1}) \\ & + \delta_h \text{ Controls} + \xi_{ijt} \end{aligned} \quad (2)$$

¹⁴ We appreciate valuable insights from industry practitioners on this matter.

¹⁵ To address the possibility that the M&A spike period may have had longer term effect on slowing down firms' market launch of major antihypertensives, we extend that period to four (1985–1988) and five (1985–1989) years in additional analyses. Findings remain fully robust.

¹⁶ In sensitivity analysis, we dichotomized this variable (Card and Krueger, 1994), capturing whether or not a firm had priority-status antihypertensives. Findings in both stages remain fully robust.

By using the 2SLS command in Stata, which performs the standard variance adjustments for the coefficient of δ_1 in the second stage, we obtain a consistent and efficient estimate for δ_1 (Wooldridge, 2002), which we use to test H1. To test the contingency effects in H2 and H3, the conventional approach is to multiply the main independent variable, competition (x_1), with the contingency variables, commercial abilities (x_2) and technical abilities (x_3), separately. However, in 2SLS estimations, this approach creates complications in the variance adjustments. For instance, in the estimated coefficient on the interaction term between competition and commercial abilities ($x_1 \times x_2$), only the portion of variance arising from predicted competition (predicted x_1) requires adjustments, while the portion arising from commercial abilities (x_2) does not. To circumvent these complications, we use split-sample analyses (Penner-Hahn and Shaver, 2005). To test H2, we split the sample by the median of commercial abilities and obtained δ_1^{LC} and δ_1^{HC} , capturing respectively the effects of competition from similar drugs in observations with low (below the median) and high (equal or above the median) levels of commercial abilities. We then perform a *t*-test¹⁷ for the difference in these coefficients to

examine if the effect of competition differs across different (low versus high) levels of the contingency variable. We follow a similar procedure to test H3.

¹⁷ The *t*-statistic was manually calculated using the formula: $t = (\delta_1 - \delta_2)/[(\sigma_1^2/n_1) + (\sigma_2^2/n_2)]^{0.5}$, where δ is the coefficient of estimated competition, σ is the standard deviation, and n is the sample size for each of the subsamples.

RESULTS

Table 2 reports summary statistics and pairwise correlations. As this table shows, on average, about 83 percent of a firm's antihypertensive-related patents involved collaborative invention. Firms in the sample faced about 10 competing similar antihypertensives in a given year. The pairwise correlations between firms' counts of antihypertensive-related patents and states (0.76), and between the time elapsed and the number of mechanisms of action (0.84) are rather high. To ensure that multicollinearity does not affect findings, we run additional models separately dropping states and mechanisms of action. Findings remain robust.

Our premise that firms readjust their collaborative invention level as a strategic response to competition implies that such level is somewhat fluid, as firms change it over time. Figure 1 plots the average of yearly within-firm changes in the collaboration ratio and shows that there is clearly variance in such within-firm changes. In other words, firms do change the extent of collaboration on a yearly basis, sometimes as drastically as 100 percent in either direction. Interestingly, for most years, both negative and positive changes occur, suggesting that firms react heterogeneously to external impetus for change.

Figure 2 illustrates changes in competition from similar antihypertensives over the M&A spike period. As mentioned, we expect firms operating in areas with major therapeutic advances to face lower levels of competition from similar drugs over this period in the mid-1980s. As this figure shows, although the total number of antihypertensives on the market increases over the period of analysis, the breakdown of competition for firms with and without priority drugs reveals patterns consistent with our expectation. Over the spike period, these two groups of firms faced notably divergent levels of competition from similar drugs, suggesting that firms did indeed hold back from launching new drugs in areas marked by major therapeutic advances, as our earlier qualitative evidence suggests. This finding lends confidence to the appropriateness of the instruments used to predict competition.

Table 3 shows results of the first stage of the 2SLS estimation. Model 1 contains control variables only. Models 2 and 3 add the instrumental variables predicting competition from similar drugs, without and with robust errors, respectively.

Table 2. Descriptive statistics and pairwise correlations

Variable	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12
1. Collaboration ratio	0.83	0.12	1.00											
2. Competition from similar	10.03	3.73	-0.06	1.00										
3. Commercial abilities	0.34	0.63	0.00	-0.43	1.00									
4. Technical abilities	0.18	0.19	0.05	-0.59	0.32	1.00								
5. Antihypertensives with different	41.20	11.90	0.44	-0.16	-0.15	0.16	1.00							
6. Antihypertensives-related	211.97	273.92	-0.07	-0.13	0.46	-0.03	-0.41	1.00						
7. Total patents	686.39	3400.71	0.02	0.02	-0.06	-0.03	-0.03	0.01	1.00					
8. States	11.70	7.20	-0.04	-0.04	0.37	-0.15	-0.26	0.76	0.03	1.00				
9. Time elapsed	13.68	5.85	0.64	0.03	0.05	-0.09	0.64	-0.02	0.01	0.07	1.00			
10. Publications in top medical	1309.72	404.06	0.26	0.01	0.07	-0.03	0.37	0.10	0.03	0.24	0.39	1.00		
11. Patents near	170.46	275.29	0.27	0.04	0.31	-0.12	-0.05	0.43	0.01	0.39	0.44	0.27	1.00	
12. Mechanisms of	5.47	0.50	0.53	0.04	0.12	-0.01	0.57	0.04	0.01	0.12	0.84	0.25	0.42	1.00
13. Litigations	15.08	24.55	0.35	0.09	-0.16	-0.12	0.46	-0.18	-0.01	-0.13	0.64	-0.03	0.07	0.54

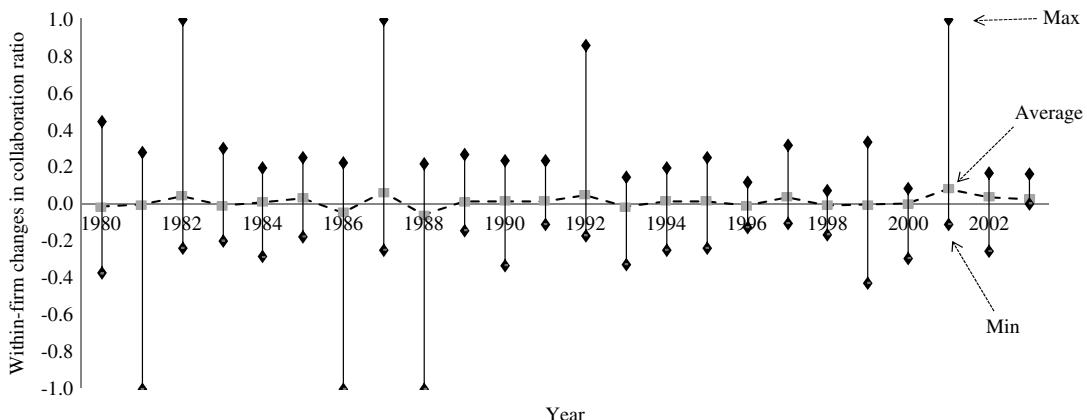


Figure 1. Within-firm changes in collaborative invention over time

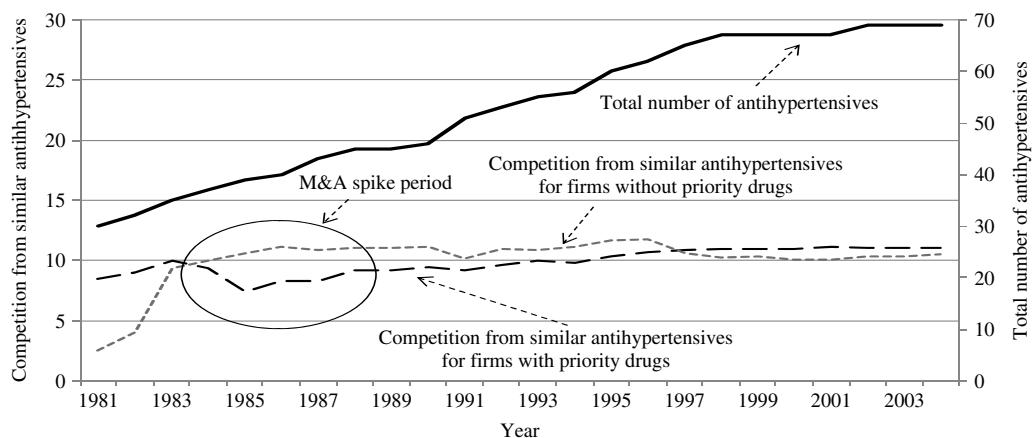


Figure 2. Competition from similar antihypertensives over time

The coefficient on the M&A spike period is generally positive in Models 2 and 3, though not significant. More importantly, the coefficient on the interaction term is significantly negative in Models 2 and 3, indicating that the M&A spike period differentially affected competition for firms operating in areas with major therapeutic advances; that is, they faced a slower rate of increase in competition during that period. This is in line with Figure 2 and consistent with our earlier rationale that the prospect of M&A induced firms to slow down on market launch of antihypertensives in areas with major therapeutic advances and to focus instead on incremental drugs launches.¹⁸

We use Model 2 to predict competition for the second stage.¹⁹

Table 4 reports second-stage estimations of influences on firms' collaboration ratio. Model 1 comprises the full sample and tests H1. Models 2 and 3 refer to the split-sample analysis that tests H2; similarly, Models 4 and 5 test H3. Models 6–10, in turn, reproduce the analyses with firm-fixed effects,²⁰ showing that the results reported below are robust.

¹⁸ In additional analysis, we apply a more stringent criterion, keeping only firms that existed both during and outside of the flux period, which further reduces sample size. First-stage findings are fully robust. Second-stage results show a

¹⁹ We also run analysis using Model 3 to predict competition from similar drugs. Results show a significantly negative influence of competition ($p < 0.10$; $z = -1.83$) and robust split-sample findings.

²⁰ This approach is highly stringent given that the M&A shock variables already account for potential omitted firm attributes when obtaining exogenous changes in competition. Moreover, the difference-in-difference estimator in the first stage based on

Table 3. First-stage regressions predicting competition with instrumental variables ($N = 247$)

	Model 1	Model 2	Model 3 ^a
M&A spike period		1.212 (1.80)	1.212 (2.33)
Priority drugs		0.0264 (0.024)	0.0264 (0.021)
M&A spike period \times priority drugs		-0.194*** (0.074)	-0.194*** (0.049)
Commercial abilities	-1.531*** -0.32	-1.616*** (0.33)	-1.616*** (0.27)
Technical abilities	-11.23*** (1.61)	-10.74*** (1.61)	-10.74*** (3.08)
Antihypertensives with different mechanisms	-0.183*** (0.029)	-0.176*** (0.029)	-0.176*** (0.036)
Antihypertensives-related patents	-0.0023** (0.0010)	-0.0024** (0.0010)	-0.0024** (0.0009)
Total patents	-0.000005 (0.000047)	-0.000002 (0.000047)	-0.000002 (0.000035)
States	-0.0533 (0.043)	-0.0451 (0.042)	-0.0451 (0.040)
Time elapsed	-0.0599 (0.11)	-0.0576 (0.11)	-0.0576 (0.12)
Publications in top medical journals	0.0038*** (0.0015)	0.0037** (0.0014)	0.0037** (0.0017)
Patents near expiration	-0.0002 (0.0009)	0.0001 (0.0009)	0.0001 (0.0007)
Mechanisms of action	2.243** (1.05)	2.187** (1.03)	2.187** (0.89)
Litigations	0.0387** (0.016)	0.0386** (0.016)	0.0386*** (0.010)
Constant	4.187 (6.14)	3.991 (6.07)	3.991 (6.36)
Year dummies	Included	Included	Included

Two-tailed tests for all variables; standard errors in parentheses.

* $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

^a Model 3 allows for robust errors.

H1 predicts that competition from rival products building on similar knowledge reduces a firm's subsequent collaborative invention involving this knowledge. In support of H1, the coefficient on competition from antihypertensives building on the same mechanism as a firm's drug (-0.035) is significantly negative in Model 1. Its economic magnitude is substantial—one standard deviation in the number of rival drugs (3.73) reduces the dependent variable by about 13 percent, which is

firm attributes (whether a firm operates in areas of potentially major breakthroughs or significant advances in hypertensive therapy) further restricts such variance required for within-firm analyses.

more than one standard deviation of the dependent variable²¹ (12 percent).

H2 predicts that the negative effect of competition on collaborative invention is greater when a firm has lower commercial abilities. Models 2 and 3 in Table 4 show the influence of competition from similar drugs for firms with low and high values of commercial abilities, respectively.²² The coefficient on competition is significantly negative in Model 2 but not in Model 3, suggesting that competition reduces collaboration more notably for firms with lower commercial abilities. In support of H2, a *t*-test of difference in coefficients of competition across Models 2 and 3 reveals that the effect of competition is indeed significantly more negative for firms with lower commercial abilities ($t = -32.39$).²³ H3, in turn, predicts that the negative effect of competition on collaborative invention is accentuated when a firm has lower technical abilities. Models 4 and 5 similarly test this contingency effect. The coefficient on competition from similar drugs is significantly negative for firms with lower technical abilities (Model 4) but not for those with high technical abilities (Model 5). Further, the *t*-test shows that such difference is indeed significant ($t = -35.05$).²⁴ This result supports H3.

It is possible that firms take longer than a year to change their collaboration in response to

²¹ Standard deviations for number of similar drugs and collaboration ratio are reported in Table 2.

²² Due to reduced sample sizes, split-sample models dropped year dummies. A concern may be that year-specific occurrences are driving our results. However, these occurrences likely affect *Antihypertensives with different mechanisms* _{$i-1$} as well, which we control for. Moreover, our 2SLS model, by restricting estimation to changes in *Competition* _{$i-1$} over the flux period, further mitigates this concern. Alternatively, we try retaining the year dummies and drop *Mechanisms of action* _{$i-1$} instead. Findings remain fully robust.

²³ A potential concern is that the measure for commercial abilities may incorporate a firm's technical abilities as well, since a drug's technical superiority also contributes to its eventual market success. We mitigate this problem by controlling for technical abilities in models examining the contingency effects of commercial abilities.

²⁴ In Models 4 and 5, the significant coefficients for "Technical abilities" with different signs across the split-samples hint that this variable may have a curvilinear effect on the firm's collaborative invention. To ensure that our findings are not affected by omission of the second-order effect of "Technical abilities," we add its square term to all models in Table 4 in a robustness test. The square term is significantly positive, indicating a U-shape for technical abilities' effect. Importantly, our findings remain fully robust with this inclusion. Alternatively, we remove "Technical abilities" from the split-sample analyses to check if its presence was driving our findings. Again, findings remain fully robust.

Table 4. Second-stage estimates of effect of competition on firm's collaborative invention

	Robustness models with firm-fixed effects									
	Commercial abilities					Technical abilities				
	Full sample	Low Model 1	High Model 2	Model 3	Model 4	Low	High	Model 5	Full sample	Commercial abilities
Competition from similar antihypertensives	-0.035*** (0.016)	-0.046*** (0.019)	0.002 (0.003)	-0.038*** (0.011)	-0.002 (0.004)	-0.025*** (0.012)	-0.069 (0.053)	-0.012 (0.008)	-0.039*** (0.019)	-0.004 (0.027)
<i>t</i> -test of difference across models	-0.061*** (0.029)	-0.000 (0.000)	-32.39 (0.010)	-0.05*** (0.047)	-0.085* (0.047)	-35.05 (0.010)	-0.007 (0.014)	-0.017 (0.000)	-13.82 (0.018)	-0.0525*** (0.034)
Commercial abilities	-0.0272 (0.20)	-1.886*** (0.88)	0.061 (1.06)	-2.800*** (0.042)	0.119** (0.054)	-0.234 (0.19)	-6.680 (4.72)	-0.121 (0.13)	-7.763** (3.89)	-0.050*** (0.096)
Technical abilities	-0.007** (0.003)	-0.006*** (0.002)	0.003 (0.001)	-0.004** (0.002)	0.002 (0.001)	-0.0012 (0.0016)	0.006 (0.006)	-0.0001 (0.003)	0.009** (0.004)	0.003 (0.003)
Antihypertensives with different mechanisms	-0.0001* (0.0006)	-0.00005 (0.0001)	-0.0004* (0.0002)	0.0001 (0.0001)	0.0001** (0.0004)	-0.0001** (0.0004)	-0.0004 (0.00056)	-0.0001** (0.0003)	-0.0002 (0.0005)	-0.0001 (0.00005)
Antihypertensives-related patents	-0.000001 (0.000002)	-0.000001 (0.000002)	0.000002 (0.000003)	-0.000003 (0.000002)	-0.000002 (0.000002)	-0.000002* (0.000002)	-0.000003 (0.000002)	-0.000001 (0.000003)	-0.000001 (0.000003)	-0.000002 (0.000002)
Total patents	-0.002 (0.002)	0.001 (0.003)	-0.001 (0.013)	-0.001 (0.013)	-0.001 (0.016)	-0.001** (0.017)	-0.002 (0.007)	-0.002 (0.007)	-0.002 (0.007)	-0.001 (0.002)
States	0.0132*** (0.0048)	0.019*** (0.005)	0.013*** (0.002)	0.016*** (0.005)	0.016*** (0.005)	0.017*** (0.003)	0.014*** (0.002)	0.018*** (0.007)	0.009** (0.004)	0.014 (0.010)
Time elapsed	0.000105 (0.000089)	0.00005 (0.00004)	0.000004 (0.00002)	0.000001 (0.00003)	0.000001 (0.00004)	0.000002 (0.00002)	0.000001 (0.00003)	0.000007 (0.00002)	0.000001 (0.00002)	0.000002 (0.00002)
Publications in top medical journals	0.0000518 (0.000037)	-0.00004 (0.00005)	0.00004 (0.00003)	0.00001 (0.00005)	0.00001 (0.00005)	-0.00001 (0.00003)	-0.0002 (0.00003)	-0.0003 (0.00002)	0.0001 (0.00001)	0.00002 (0.00001)
Patents near expiration	0.0637 (0.058)	0.004 (0.040)	-0.001 (0.023)	-0.016 (0.035)	-0.049* (0.029)	-0.001 (0.029)	-0.002 (0.029)	-0.002 (0.029)	-0.0003 (0.029)	-0.0002 (0.029)
Mechanisms of action ^a	Litigations	0.001 (0.0009)	0.0001 (0.0005)	-0.001 (0.0006)	0.0005 (0.0004)	0.0003 (0.0006)	0.0003 (0.0006)	-0.0003 (0.0006)	-0.0003 (0.0006)	0.0002 (0.0005)
Constant	0.925*** (0.27)	1.489*** (0.32)	0.721*** (0.093)	1.615*** (0.270)	Not Not Included	1.939** (0.120)	1.939** (0.13)	1.939** (0.90)	1.696*** (0.10)	0.553*** (0.065)
Year dummies	Included	Included	Included	Included	Included	Included	Included	Included	Not Included	Not Included
Observations	246	175	71	131	115	246	175	71	131	115

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; two-tailed tests for all variables; standard errors in parentheses.
^a Models 6–10 do not contain variable "mechanisms of action" due to reduced within-firm variation.

competition. As robustness checks, we add two-year lag, and separately two- and three-year lags, of competition to all models in Table 4, and test for joint significance of all lags in each model. In the split-sample, we test for differences in the joint lags across models (Model 2 versus 3, and Model 4 versus 5). All results remain robust. It is also possible that different mechanisms of action that firms use come with different availability of IP protection and scientific knowledge, in ways that confound our findings but are not captured by our control variables (rivals' litigations and scientific publications). Additional analyses adding dummy variables for mechanisms of action showed robust results.

Validity of patent coauthorships as a measure of collaborative invention

Notwithstanding our earlier justifications of patent coauthorship as a valid measure of collaborative invention, we conducted a variety of supplemental analyses to further examine such validity. Specifically, we examine the possibilities that firms may reduce patent coauthorships for strategic reasons, that coauthorships may be picking up firms' overall inventive effort, or that other structural factors may exist that influence coauthorships.

First, one may conjecture that a firm lists on a patent only the inventor who most contributed to an invention, in fear of rivals' attempts to invalidate the patent by challenging the contributions of coinventors. Such possibility should be more pronounced when rivals are litigious, and our analyses control for rivals' litigiousness. Additionally, we examine the relationship between the number of inventors listed on patents and the nature of inventions underlying patents. Our premise is that inventions involving more inventors typically entail greater search scope. This alternative conjecture would suggest that such a relationship would not be observed, since collaboration may have actually occurred even in what one observes as a solo-inventor patent. We reconstruct the database at the patent level, and trace, for each patent, the patents that it cites and identify their USPTO-assigned technology classes. Next, we run a series of regressions to test the effect of the number of inventors listed in a patent on that patent's search scope (i.e., unique technology classes it cited). Findings in Table 5 show a persistent positive effect across models; that is, the greater the

number of inventors listed on patents, the wider the search scope. This finding provides additional evidence that inventors listed on patents do correspond with collaboration underlying the invention process, contrary to the conjecture that firms are strategically listing fewer inventors on patents.

We further examine this conjecture by checking authorships on scientific publications associated with patents. The logic is that firms are less likely to strategically manipulate authorships on scientific publications, since these do not face the same risk of subsequent invalidation that patents face. The patent experts we consulted raised a potential issue that scientific publications about an invention may very well comprise authors who are not coinventors of the respective patent. For example, an individual who collaborates in other phases of an invention beyond its conception may qualify as a coauthor in a publication about the invention, but does not qualify as a patent's coinventor.²⁵ This issue notwithstanding, evidence that scientific publications associated with a solo-inventor tend to have a limited number of coauthors should help mitigate the concern. We identify 49 solo-inventor patents in our sample and search for matching scientific publications for each of these patents, following the patent-paper matching procedure adopted in prior work²⁶ (Murray, 2002). We find matching scientific publications to only four solo-inventor patents. This is not surprising, given that inventions with solo-inventors tend to be narrower in scope and thus less likely to warrant a novel scientific contribution. Importantly, in only one of these cases did the inventor of a patent have another collaborator from the same department as coauthor of the associated publication. This evidence bolsters confidence that solo-author patents are not associated with larger collaborative efforts.

A related issue is that firms may split the outcomes of a large collaborative project into multiple solo-inventor patents, despite the abovementioned legal considerations. This interpretation suggests

²⁵ An individual who implements an inventive idea or participates in its reduction to practice may qualify as a coauthor in a scientific publication, but not as a coinventor of the respective patent (USPTO, 2012).

²⁶ Murray (2002) proposed a single patent-pair match; that is, she linked patent 5,041,138 (neomorphogenesis of cartilage *in vivo* from cell culture) to a publication by Vacanti *et al.* (1991). Our procedure involved identifying all scientific publications (co)authored by the inventor of each patent, followed by analysis of patent and publication abstracts to ascertain whether their contents overlapped.

Table 5. Patent-level effect of number of inventors on search scope

	Model specification					
	Negative binomial with year dummies	Negative binomial with year dummies, robust errors	Negative binomial with year and technology class dummies	Poisson with year dummies	Poisson with year and technology class dummies	Random-effects Poisson with year dummies
Number of inventors on patent	0.0153*** (0.0033)	0.0153*** (0.0035)	0.0149*** (0.0033)	0.0153*** (0.0033)	0.0149*** (0.0033)	0.0153*** (0.0033)

Two-tailed tests for all variables; standard errors in parentheses. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

these firms will have more patents, all else equal. Our analyses address this issue by controlling for a firm's number of antihypertensive-related patents, as well as a firm's total patents (spanning beyond antihypertensive therapy). Further, we consider that, if our proposed effect of competition on reducing collaboration is only driven by firms splitting collaborative projects into multiple solo-inventor patents, then this effect will likely disappear in a subset of firms with a higher number of patents. We split the sample along the median of firms' antihypertensive patents in a previous year, retained the subsample of firms with more patents, and rerun the analyses.²⁷ Findings remain fully robust, further assuaging this concern.

A potential concern is that the measure for collaborative invention might simply reflect a firm's inventive effort. For instance, a firm might list inventors on the same patent even when the inventors separately create the same invention without collaboration. This is more likely to happen when a firm's overall inventive effort increases, which stresses the need to control for inventive effort. As we clarified earlier, our analyses control for both a firm's antihypertensive-related patents, as well as total patents. Also, we find that the pairwise correlation between the collaboration ratio measure and a firm's number of antihypertensive-related patents is 0.0047 and nonsignificant ($p > 0.10$). This provides reasonable assurance that a firm's inventive effort is likely not confounding our dependent variable. Furthermore, if our findings are only driven by inventive effort, then our findings should diminish in the subset of firms that are unconstrained, that is, have a large number

of total patents. However, we have shown that our findings remain robust in the subset of firms with a higher number of patents (see earlier issue). We further entertain the possibility that increased R&D expense may increase a firm's number of inventors, which increases the likelihood of inventors coming up with the same idea and hence the incidences of patent coauthorship without actual collaboration. We control for a firm's number of inventors involved in antihypertensives in a robustness test. Findings remain fully robust.

Another concern is that, despite the legal requirements for inventors listed on patents, coauthorships might in a few cases reflect a hierarchical structure where managers' names appear in patents even when they did not substantively contribute to the inventions. This scenario likely does not confound our findings, as it is not clear why this inclusion would systematically vary with the relative change in competition between different types of firms over the M&A flux period. Further addressing this concern, we note that if coauthorships indeed reflect managers' inclusion in patents, then a firm operating with more mechanisms of action within antihypertensives and hence needing more managers to coordinate across them should exhibit greater coauthorships. We include a firm's number of mechanisms of action in the second-stage estimation (Table 4) in a robustness test, and find that, in the full model, the coefficient on such variable is in fact significantly negative ($z = -2.20$) rather than positive. All earlier findings remain robust, providing additional assurance that this conjecture does not affect the findings.

Finally, although our research question about collaboration versus solo inventors is best tested with a dependent variable capturing the proportion of collaborative inventions in a firm's patents,

²⁷ Due to the reduced sample size, the year dummies are dropped from the second-stage estimation.

the mechanisms underlying our propositions can arguably be extended to explain team size in collaborative invention as well. Specifically, the greater need for search depth and invention speed that competition spurs may induce a firm to choose fewer inventors in collaborative projects. As a robustness check, we replace the dependent variable with the average number of inventors on a firm's relevant patents in the observation year. This dependent variable has a mean and standard deviation of 2.87 and 0.91, respectively, and ranges between 1 and 9.4. The coefficient of competition remains negative ($p < 0.1$), and the split-sample tests remain fully robust ($t = -25.17$, $p < 0.01$ for H2 and $t = -25.11$, $p < 0.01$ for H3).

DISCUSSION AND CONCLUSION

Our central proposition is that competition from similar products diminishes a firm's propensity to engage in collaborative invention. Greater collaborative invention corresponds with more exploratory search and requires more time for a firm to overcome the attendant collaboration difficulties. Competition from similar products compels a firm to favor search depth over exploratory search and to respond expeditiously, thereby pushing it away from collaborative invention toward having its inventors work more individually. Furthermore, we argue that this main effect is more prominent when a firm is weaker in commercial or technical abilities, because such weaknesses diminish the attractiveness of exploratory search and aggravate a firm's time pressure to respond to competition. In support of our central proposition, we find that the greater the number of rival antihypertensives building on the same mechanism of action as a firm's antihypertensive, the less that firm engages in collaborative invention involving knowledge of that mechanism. Findings also show that this effect of rival drugs is accentuated when that firm lacks commercial or technical abilities.

Implications for management practice

This study furthers our understanding of challenges that managers face when organizing inventive effort. From a managerial standpoint, prior research stressing the benefits of collaborative invention may have been taken as a message for managers to always foster collaboration

between inventors. We stress in contrast that collaborative invention is not a universally superior practice. Instead, managers can exercise considerable discretion over how to organize their inventors so as to balance the tradeoff between the benefits that collaboration produces and the additional difficulties it entails. Importantly, a firm's idiosyncratic situation affects such tradeoff. As our findings reveal, the level of competition that a firm faces plays a substantial role in explaining variations in the level of collaborative invention. Specifically, with intense competition, managers move away from collaboration toward solo inventions. While this forgoes benefits of collaborative invention, it ensures timely and pointed responses to the high technical bars that have been raised as rivals become increasingly entrenched in a particular technology. Conversely, when a firm faces less intense competition, managers are in a better position to take on collaboration difficulties in exchange for a broader array of potential knowledge combinations.

Theoretical contributions and opportunities for future research

This study has significant implications for the firm heterogeneity puzzle at the core of strategy research. In examining why firms in the same product market perform differently, scholars proposed that downstream performance differentials arise from a nonuniform distribution of upstream firm-specific resources (Barney, 1991, Wernerfelt, 1984). To explain this distribution, prior studies have examined how firms search for resources differently (Ahuja and Katila, 2004) and how they organize their upstream inventive activities to facilitate this search (Nickerson and Zenger, 2004). The implicit approach along this vein is to attribute resource differences to some other form of organizational heterogeneity upstream, ultimately tracing upstream heterogeneity to some form of initial endowment differences at firms' inceptions. This study, in contrast, reverses the focus from preexisting upstream heterogeneity to competition in downstream markets as a driver of resource heterogeneity across firms. Such reversal is theoretically meaningful because it potentially circumvents the need for researchers to perpetually search upstream for the seemingly elusive source of heterogeneity. Rather, it suggests that perhaps firm heterogeneity is really shaped by how downstream

competition unfolds at various points in time for each firm.

Besides offering a different approach to explain how firm heterogeneity arises, this study also raises questions about why firm heterogeneity persists. Equally puzzling as the origin of firm differences is the persistence of such differences. Dissimilar firms within an environment do not always converge subsequently toward homogeneity. Conceptually, for convergence to occur, there must either be resource transfer across firms or firms must independently create similar resources subsequently. To explain why resource transfer or imitation can be difficult, prior studies have argued that resources are "sticky," and organizational features such as complexity further impede resource transfer (Liebeskind, 1996; Rivkin, 2000). With respect to why firms do not subsequently create similar resources, predominant explanations center on firms' tendencies toward path dependence and local search (Cyert and March, 1963), due to bounded rationality, inertia, and routines (Nelson and Winter, 1982). This study, in turn, hints at an alternative approach to explain this persistence, by showing how a firm's commercial or technical abilities affect its response to competition. When competition causes a firm with weaker abilities to reduce more of its exploratory search, this firm may be compromising its inventive potential and subsequent abilities in the long run, which ironically renders it more vulnerable to competition in the future. Consequently, as competition pushes firms with differential abilities further apart, small initial differences in abilities may spiral into significant heterogeneity over time.

This study prompts further questions about how else firms may engage in exploratory search. Our main proposition is that competition reduces firms' priority and feasibility of exploratory search and shifts their focus away from collaborative invention toward greater search depth. Yet, it is possible that a firm facing competition, while diminishing its exploratory search via collaborative invention, may turn to other avenues of exploratory search, such as alliances, licensing, or tie-ups with universities, in ways that entail less commitment of resources.

Another avenue for future research is to examine the extent that our propositions are applicable across industries. Our propositions presume a firm's ability to identify rival products building on similar knowledge. In many industries, competing

platforms, paradigms, or fundamental technologies are indeed clearly identifiable. Yet, there are plausibly other instances, such as during early stages of a technology, where the boundaries of platforms are not clearly defined. In these instances, firms might be unable to observe if rival products are eroding market opportunities and requiring them to engage in search depth as we theorize. Further, our study examines a setting where patent protection is relatively strong. Arguably, the effects of competition that we theorize are even stronger in contexts where firms cannot rely on patents to deter the emergence of similar products and are thus exposed to greater levels of competition. We encourage future research to explore firms' collaboration propensities in these instances.

Finally, this study points to opportunities for future research on how competition, a central construct in strategy research, affects firms. Prior research has highlighted competition's impact on firms' decisions regarding what markets to enter and how much inventive effort to invest in these markets. However, researchers have largely neglected the next step of examining how competition affects a firm's use of its inventors' existing knowledge to create new knowledge. Addressing this gap may be crucial as such process determines a firm's resource accumulation and consequently a firm's growth (Penrose, 1959). Through this paper, we hope to kick start this examination. A potential point of departure from existing research is that competition does not drive a firm out of a market or force it to give up its existing knowledge within this market. Rather, it induces a firm to reorient its approach toward exploiting this knowledge.

In sum, by showing that competition influences whether a firm utilizes its individual inventors more as a collection of solo inventors or closer to a set of collaborative inventors, this study indicates fecund research opportunities on firms' utilization of knowledge and their resulting processes of resource accumulation and growth. We believe that by reversing prior research's focus on how upstream resources influence a firm's position in downstream markets and also by considering how downstream competition shapes a firm's upstream resource utilization, we can attain a more comprehensive picture of how firms develop and accumulate resources. We hope that the possibilities we delineated above will stimulate such stream reversal in future studies, leading to

better understanding of the origin and persistence of firm heterogeneity.

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