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Knowledge Development Approaches and Breakthrough Innovations in Technology-Based New Firms*

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Compared to large established firms, technology-based new firms (TBNF) seem well placed to produce breakthrough innovations although questions remain as to their adeptness at subsequent exploitation. Building on the innovation and strategy literatures, the study identifies two different knowledge-development approaches or modes (business models) in TBNFs—internal versus external—and examines their relation to breakthrough innovation and subsequent progression of the product to market. The internal mode assembles knowledge inside the firm to generate its innovations, whereas the external mode relies heavily on alliances to develop and assemble knowledge among firms embedded in a creative network. The study uses a unique panel dataset of 69 UK new biotechnology firms over an 11-year period to explore this issue empirically. The findings show that the external knowledge-development mode is associated with more breakthrough innovations and a faster movement of innovations to market. The externally focused mode is not impeded by its relative lack of internal knowledge; it uses partners to access, assemble, and develop a wide scope of knowledge in a flexible manner. In addition, partners provide deep domain expertise to undertake the requisite deep-dives. In contrast, the internal mode has the huge challenge of assembling knowledge resources internally and suffers from a quicker onset of path dependence that impedes the generation of breakthroughs. This study provides a choice of business models (internal or external) that is associated with different breakthrough and speed to market performance outcomes. Going forward, policy makers and managers seeking breakthrough innovations, and speedy progression of the innovations to market should consider the potential resource efficiency of the external mode and the vital role played by collaborations—small firm versus large firm and private versus public entities.

Practitioner Points

- In organizing for breakthrough innovation, firms are faced with a choice between external or internal knowledge-development approaches

- The external mode is better at achieving breakthroughs as well as speedily progressing products under development to market
- The advantages of the external mode are resource efficiency and flexible access to knowledge of partners
- The internal mode's performance is hampered by its need for substantial resources and the relative lack of flexibility

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Introduction

As noted by Colombo, Rossi-Lamastra, Stephan, and van Krogh (2015), large, established incumbent firms confront severe obstacles when engaging in the development of breakthrough innovations (Christensen, 1997; Henderson, 1993). This means smaller and newer firms are expected to fill the gap. There is a particular group of small firms that hold special interest—technology-based new firms (TBNFs)—that are found in many locations, including

Silicon Valley and Cambridge, USA, and Cambridge and London, UK.

TBNFs should be well placed to produce breakthrough innovations because they are relatively more creative and free from the inertia and myopia of their larger counterparts (e.g., Schneider and Veugelers, 2010). Yet, organizing for breakthrough in dynamic markets, such as in biotechnology, is challenging for TBNFs because it requires deep domain expertise to undertake deep-dives and to assemble and develop a wide scope of knowledge—usually from disparate sources (e.g., Kaplan and Vakili, 2015; Phene, Fladmoe-Lindquist, and Marsh, 2006). To handle all the necessary development required for breakthrough, TBNFs look to re-combinations of internally and externally sourced knowledge (e.g., Carayannopoulos, 2009; Powell, Koput, and Smith-Doerr, 1996).

Even though all TBNFs use alliances to source external knowledge, what is not clearly understood is

whether in organizing for breakthrough TBNFs should focus their creativity more toward internal or external knowledge. The second question that is unclear is which organizing approach, given the resource mobilization challenge that underpins each organizing approach, allows TBNFs that successfully produce breakthrough innovations to also progress products faster toward the market. This question arises from the tension highlighted by March (1991), that successful exploration in generating breakthrough innovations may be far removed from successful exploitation, i.e., bringing products to market quickly.

Grant (1996) and Grant and Baden-Fuller (2004) note that there are two fundamentally different “knowledge-development approaches or modes” among firms that are involved in alliances. These modes differ in terms of their loci of creativity and the way knowledge is assembled and, hence, are likely to yield quite different knowledge outcomes. For the case of TBNFs, the first organizational approach that we label “internal mode” involves efficient knowledge integration by organizing multidisciplinary R&D capabilities within the boundaries of the firm under hierarchical control, deemed to save coordination costs and limit expropriation concerns (e.g., Cassiman, Di Guardo, and Valentini, 2005; Chesbrough and Teece, 1996; Grant, 1996; Spithoven, Frantzen, and Clarysse, 2010). Despite its small size and relative newness, a TBNF can successfully adopt this mode focusing on internal R&D, supplemented where necessary by external knowledge typically gained in alliances.

In contrast, the other less-explored “external mode” avoids large commitments to in-house R&D and in-house laboratories. Instead, the firm engages external partners for almost all development work, including both the assembly of knowledge and its development, and it uses creative organizational arrangements to mitigate the anticipated high transaction costs and risks of loss of control (e.g., Grant and Baden-Fuller, 2004; Lorenzoni and Baden-Fuller, 1995). The external mode, typically labeled virtual or hollow, requires a rich network of partners that hold and develop the necessary knowledge. The existing literature on innovation has tended to down-play the importance of this second approach—citing issues of opportunism and coordination costs (see for instance Cassiman et al., 2005; Chesbrough and Teece, 1996)—yet for the TBNFs seeking nonstandard outcomes such as speedy breakthrough innovation, the knowledge access approach may be very attractive because of the lower commitment, greater flexibility, and the possibility of accessing knowledge over a wider domain.

BIOGRAPHICAL SKETCHES

Dr. Dzidziso Samuel Kamuriwo is a senior lecturer in strategy at Cass Business School, City, University of London. His research focus is knowledge and innovation strategies using alliances and acquisitions. His other research is on board-level knowledge and network strategies and how they relate to important business outcomes including innovation and economic performance. His research has been published in leading innovation and management, journals including, among others—*Research Policy* and *Leadership Quarterly*. Dr. Kamuriwo holds an MBA and PhD in Management from City University of London, Cass Business School.

Dr. Charles Baden-Fuller is the Centenary Professor of Strategy and leader of the Strategy Group at Cass Business School, City, University of London. He is famous for his strategy insights into the management of mature firms, his work on networked organisations and the management of young high technology firms. More recently, he has become one of the leading global thinkers on the topic of Business Models: what they are, how they work, how they can be improved, and how they can be deployed in an increasingly digitalized world. This work is supported by substantial research grants and a team of academics based at Cass Business School, Sussex University, LSE, CREATE-Glasgow, Grenoble EM, and the Wharton School. Charles is a fellow of the Strategic Management Society and fellow of the Academy of Social Sciences.

Dr. Jing Zhang has been an assistant professor in management, Strome College of Business, Old Dominion University since 2012. Her research spans entrepreneurship, technological innovation, and knowledge management. She has published more than 20 refereed publications in journals such as *Entrepreneurship: Theory and Practice*, *Journal of Business Venturing*, *Journal of Management*, *Journal of Management Studies*, *Journal of World Business*, *Strategic Entrepreneurship Journal*, and *Research Policy*. Before coming to ODU, she gained her PhD from National University of Singapore, and worked at Iowa State University (US), Lancaster University (UK), and City University London (UK) as well as with Lenovo Co. (China). Dr. Zhang is a member of AIB, AOM, and IACMR.

In the theory development section, hypotheses are formally developed relating the two modes of organizing knowledge to breakthrough innovation and subsequent exploitation in product development. Using the knowledge-development and innovation literatures, the paper looks at how each mode influences the way in which key prerequisites for breakthrough innovation, i.e., the assembly of distant and diverse knowledge and the undertaking of deep-dives (e.g., Kaplan and Vakili, 2015; Phene et al., 2006), are organized. Even though TBNFs are generally considered relatively flexible (e.g., Schneider and Veugelers, 2010), the relatively quicker onset of path dependency in the internally focused mode as the TBNF grows presents problems that may limit the possibilities of breakthrough innovation and fast product development (e.g., Cohen and Levinthal, 1990; Ghemawat and del Sol, 1998; McGrath and MacMillan, 2000; Padgett and Powell, 2003; Puranam, Singh, and Zollo, 2003; Rothaermel and Deeds, 2006). The paper suggests that the external development mode will be more successful at breakthrough innovation and the related product development because the richer network arrangement is associated with flexibility and “option-like” characteristics, which allow the TBNF to probe the unexpected without the extensive commitments and path dependency associated with the internal development mode (McGrath and MacMillan, 2000).

The setting of new drug development in biotechnology is used to explore the validity of our theorizing. The unique dataset includes 69 UK biotechnology firms’ knowledge-development modes and product innovation over an 11-year period from 1995 to 2005. The empirical work supports the theoretical propositions. The findings are that after controlling for important environmental factors, particularly funding levels, the externally focused development mode is associated with superior breakthrough outcomes and related product development.

It is revealing to selectively compare two quite well-known firms in the database: Arrow (a firm with an internal knowledge mode) and Alizyme (a firm with an external knowledge mode), both of which were carefully interviewed by the first author. Arrow was founded around 1998 and raised approximately £40 million by the end of 2005. It engaged in ten alliance partnerships, seven of which took place in the first two years of its life. Adopting an internal knowledge-development mode, Arrow integrated alliance partners’ knowledge into its own laboratories. Its achievements by the end of 2005 include two U.S.

patents, one project passing Phase I clinical trials, and several others in the pipeline. However, none of Arrow’s patents can be considered a “breakthrough.” In contrast, Alizyme, founded in 1997, raised £59 million by the end of 2005 and never built a lab and did not employ “wet bench” scientists but engaged in 18 alliances. Alizyme won six U.S. patents (from work that was subcontracted to partner firms), and one of these patents was a “breakthrough” (a potential blockbuster anti-obesity drug). Additionally, Alizyme had projects passing Phase I clinical trials faster than Arrow. Founded at similar times, with similar levels of funding, Arrow (internal mode) was less productive compared to Alizyme, as Arrow, in particular, did not achieve any breakthrough patents.¹

This study extends the strategy perspective of innovation management by identifying how two different knowledge-development approaches that can be adopted by TBNFs influence breakthrough innovation and subsequent product development.

Theoretical Framework

The topic of this special issue is breakthrough innovations, defined as high-impact innovations (Conti, Gambardella, and Mariani, 2014; Kaplan and Vakili, 2015; Phene et al., 2006) or products “that create entirely new markets or radically change existing ones” (Colombo et al., 2015). It is typically argued that producing breakthrough innovation involves recombination of distant and diverse knowledge bases (e.g., Cassiman et al., 2005; Kaplan and Vakili, 2015) and the ability to explore complex issues with a deep-dive into a specific arena (e.g., Padgett and Powell, 2003; Weisberg, 1999). Below, the features of external and internal knowledge-development modes are first articulated, particularly how the modes organize the assembly and subsequent development of knowledge for breakthrough innovation. Then, the hypotheses on how the knowledge-development modes relate to breakthrough innovation and product development rate will be presented.

External Development Mode

The externally focused knowledge-development mode is associated with more virtual organizations (Chesbrough and Teece, 1996), network organizations (e.g.,

¹Neither firm exists today—their patent portfolios have been absorbed into other firms.

Miles and Snow, 1986) or modular organizations (Sanchez and Mahoney, 1996). The knowledge base of the firm lies mainly outside its boundaries, with the founders and top management team holding a complementary base of expertise. In the case of TBNFs, their teams typically include star scientists with managerial experience drawn from within the biopharmaceutical industry (e.g., Powell and Sandholtz, 2012). The external mode firm, through its founders and managers, plays an integrative role in a network of partners organized to assemble and develop knowledge. The focal firm role involves raising money, helping with the design of studies in collaboration with partners (but not having wet bench scientists), in-licensing of IP for further development, developing the network by recruiting partners (e.g., providing leadership that includes getting buy-in on the innovation concepts from potential partners, making use of industry contacts and experience in recruiting partners) and managing the network (i.e., providing an overall governance structure and coordination to facilitate knowledge sharing and development and, finally, project managing the product development process from stage to stage), (Kamuriwo and Baden-Fuller, 2016).

Why should partner firms cooperate and engage in such knowledge assembly? Why should they engage in the deep-dives required for innovation and give up the intellectual property (IP) rights to the final product? Partner firms are specialist firms that provide either specialist or complex services that are usually for only a segment of the value chain. For example, the biotech value chain is lengthy and has distinct product development stages. Partners are recruited to provide specialist services, such as chemistry services providers or specialist testing laboratories. Other partner firms provide more-complex services, which may cover a distinct value chain stage (Kamuriwo and Baden-Fuller, 2016). The motivation to participate goes far beyond cash or future option payments. Some partners are motivated by being part of a much more valuable network of firms in which the focal firm can add value by communicating and transferring knowledge gained across the network (e.g., Nambisan and Sawhney, 2011; Kamuriwo and Baden-Fuller, 2016). Large incumbents have knowledge already assembled for another purpose—where the knowledge is not being fully utilized or is quite complementary to that of the focal firm. Thus, large incumbent firms may perceive partnering with TBNFs as a highly profitable use of already assembled knowledge as well as an opportunity to learn new things by participating with others

that have different perspectives on challenging issues (Lipparini, Lorenzoni, and Ferriani, 2014; Lorenzoni and Baden-Fuller, 1995).

The process by which the focal firm assembles knowledge is quite different from its internally focused counterparts. It assimilates, or “accommodates” in the terminology used by Todorova and Durisin (2007), knowledge through external mechanisms with no primary intention to integrate external knowledge internally (e.g., Grant and Baden-Fuller, 2004). These processes involve network development that avails relevant diverse knowledge to the focal firm for product development (e.g., Chakma, Calcagno, Behbahani, and Mojtahedian, 2009; Nambisan and Sawhney, 2011).

In making the above points, we recognize that many have criticized the capacity of virtual arrangements to achieve success in any dimension. The criticisms relate to many issues, such as interfirm transaction costs and risk of loss of control (e.g., Chesbrough and Teece, 1996), opportunistic risk and other transaction costs associated with arm’s-length contracting (Hagedoorn and Narula, 1996), entrepreneurs underestimating the difficulty of running the external mode (Gulati and Kletter, 2005), and externally oriented firms being overtaken by their competitors (Askenazy, Thesmar, and Thoenig, 2006). These concerns may be overestimated because the well-organized externally oriented firm develops defense mechanisms to minimize such risks. These mechanisms may include owning the specific intellectual property rights (IPR) on the innovations they purchase and ensuring that the large firms gain from the transaction to leave them satisfied (e.g., Katila, Rosenberger, and Eisenhardt, 2008). To fully appreciate the external mode, it is valuable to explicate the alternative approach.

Internal Development Mode

The internal development mode is typically associated with large incumbents and, in this context, with smaller and newer firms that closely follow the structures and processes of large firms. It involves assembling, exploring, and exploiting knowledge within the boundaries of the firm to ensure efficient management of dense transactional knowledge flows and cross-domain linkages normally associated with deep-dives required in breakthrough innovation (e.g., Brusoni and Prencipe, 2011; Padgett and Powell, 2003). It also involves developing routines for evaluating, acquiring, and exploiting external knowledge that fills knowledge gaps—a process called absorptive capacity (e.g.,

Cohen and Levinthal, 1990). The basic premise of an internally focused mode is that the firm develops deep domain expertise and engages in the necessary deep-dives and knowledge integration activities that produce breakthroughs (cf. Pammolli, Magazzini, and Riccaboni, 2011; Weisberg, 1999). In this context, the firm needs a set of “higher-level organizing principles” and a conducive social context to support its knowledge management activities (Grant, 1996; Kogut and Zander, 1996). These principles outline what has to be done and, importantly, smooth away internal impediments (such as haggling and turf wars) through fiat-based mechanisms (e.g., Conner and Prahalad, 1996).

The principles that underlie these outcomes are a strong commitment to assembling diverse knowledge internally (perhaps with alliances), exploring that knowledge (with deep-dives) and then exploiting that knowledge (e.g., Weisberg, 1999). A firm requires deep domain knowledge to understand the foundational assumptions of knowledge domains, and this knowledge includes knowledge of weaknesses that may need to be overcome to achieve breakthrough innovations (Taylor and Greve, 2006).

However, there is an important additional issue that arises where knowledge covers a wide terrain and where that knowledge within these different spheres evolves at different speeds. In such cases, the firm has to make choices about which knowledge to assemble and where to take the deep-dives, and these choices may give rise to path dependency, shutting out some possibilities but increasing others. This onset of path dependency (focus) has potential negative effects for achieving breakthrough innovation because it tends to move the firm forward based on the refinement of relatively well-known paths (Sørensen and Stuart, 2000) or on the basis of making use of well-known heuristics (Chase and Simon, 1973), all of which reduces the likelihood of using “outside the box approaches.” In addition, the small TBNF following this internal mode can be seriously challenged to assemble the necessary knowledge to innovate—it may take time and money to assemble the knowledge and build the relevant processes (e.g., Powell et al., 1996; Sapienza, Autio, George, and Zahra, 2006). Only those TBNFs that wisely choose their knowledge terrain can be successful.

Knowledge Development Modes and Breakthrough Innovations

As noted above, the internal mode of knowledge-development encourages dense transactional knowledge flows

and cross-domain linkages that aid breakthrough innovation (e.g., Brusoni and Prencipe, 2011; Padgett and Powell, 2003). However, the internally focused knowledge-development mode commits early to a technology approach and limits future search breadth. This commitment leads to path dependency, which is reflected in the subsequent development of knowledge-sharing processes, routines, shared communication codes, and culture (Cohen and Levinthal, 1990). All of these factors make the internally focused business model relatively less flexible (Leonard-Barton, 1992; Zahra and George, 2002). Put another way, the internal mode is likely to be associated with a narrow scope, fixed purpose, and limited search that makes the firm’s knowledge base “sticky” and its direction difficult to reverse. Thus, although the internal mode may create breakthrough innovation in its chosen path, it has a relatively limited capacity to achieve the necessary variation to support a number of breakthrough innovations, especially in fast-moving markets.

In contrast, the externally focused knowledge development mode has more flexibility than the internal mode because, for example, the firm’s value chain activities or its components can be more easily disengaged or recombined in different ways to react to different opportunities (Schilling and Steensma, 2001). This means that the external mode can generate more options that allow the search to range over a far wider area (Grant, 1996; McGrath and MacMillan, 2000) and is less likely to suffer from the onset of core rigidities than the internal mode (Leonard-Barton, 1992). Therefore, firms with the external mode will retain a greater willingness and ability to act on new knowledge. With the external mode, it is not the firm but the partner who provides the majority of the resources (including the absorptive capacity; Cohen and Levinthal, 1990). Thus, although the focal firm shows a relative lack of commitment, the amount of resources in the whole system may be higher than that in the internal mode, giving rise to more breakthrough innovations (Lipparini et al., 2014; Lorenzoni and Baden-Fuller, 1995).

As noted above, it is not sufficient to merely note the possibility of combinations—the firm has to engage in deep-dives to make the combinations happen. Here, the externally organized firm is challenged because the deep-dives often have to be undertaken by partners. However, this is possible. The history of ARM, the UK microchip design company that has won more than 90% of the world’s mobile phone market through external knowledge development, is an

illustration of just these points. It has used its partners to search over a wide domain, and it has used its partners to deep-dive and make the new combinations work. O’Keeffe and Williamson (2002) and subsequent shareholder presentations and annual reports document some of the processes adopted by ARM, as well as how the firm achieved a series of breakthrough innovations.

H1: Other things being equal, the externally focused knowledge development mode will achieve more breakthrough innovations than the internally focused mode.

Knowledge Development Modes and Product Development

When considering the organizational arrangements that favor breakthrough innovations, it is also necessary to consider the issue of timely and prompt exploitation. Society as a whole, and investors in particular, are impatient. It was March (1991) who pointed out that tensions between effective exploration and timely exploitation can often hinder firm success; and it was Teece (1986) who emphasized that firms that engage in the greatest breakthrough innovation are challenged to exploit those benefits in a timely manner, citing examples of 19th century innovators such as Eli Whitney dying in penury before he could reap the benefits of his highly successful cotton-gin invention. Carayannopoulos (2009), among others, explains that the chances of successful exploitation of breakthrough innovations are strongly influenced by whether innovation challenges the industry assumptions about architecture and modularity, with far greater chances of success for those that are not challenging the status quo on many dimensions. The context here, like so many, is one where breakthroughs are radical but do not necessarily require changes in the industry’s architecture. Regulatory constraints force all drug development firms, no matter how groundbreaking the drug, to yield to clinical testing and use established channels of distribution. Yet, there is still a gap between the breakthrough innovation (typically represented by a successful patent) and ultimate success—which can only be bridged if the firm puts its innovation into a product that can be launched in the market. In the context of this paper, it is therefore possible that one mode of knowledge development may favor developing an innovation but be paradoxically less effective at putting innovations on the market.

The two modes of organizing—external and internal knowledge development—have different implications for how (scarce) resources are allocated toward progressing products under development to market (e.g., Conti et al., 2014). The internal mode is associated with a large firm mentality and relatively slow internal knowledge sharing. Typically attributed to functional silos, these barriers keep the R&D laboratories separated from business development units (Tsai, 2002).

In contrast, a TBNF that adopts the external model is likely to move faster, because the external mode is based on quick and flexible access to relevant distant or diverse external knowledge in specialized partners or large established organizations. The functional silo issue is also much less evident in the external mode. Moreover, while having diverse domains in-house may be good for creative tension, it may also create serious problems such as divergent objectives, domains competing for organizational resources, and high coordination costs across domains (Lerner and Merges, 1998).

The strategic logic of the externally focused knowledge development mode also allows for quick access to new resources or new knowledge, particularly in fast-paced environments (Kamuriwo and Baden-Fuller, 2016; Volberda, 1996). Just as the internally focused knowledge development mode is associated with earlier commitment, the external mode offers flexibility that is associated with keeping choices open and thus affords strategic flexibility or speed to change course, a style that is associated with flexible options (McGrath, 1999; McGrath and MacMillan, 2000, esp. chapter 11). Hence, adopting a virtual business model, firms with the external mode become more reactive and sensitive to customer needs, and they will achieve faster product innovation compared to firms with the internal mode.

H2: Other things being equal, for firms that have achieved breakthrough innovations, the externally focused knowledge development mode will be associated with a higher product development rate than the internally focused mode.

Methodology

Research Setting, Data, and Sample

The biotechnology sector is associated with breakthrough innovations (Lazonick and Tulum, 2011). Novelty is the objective of all drug development R&D

programs because new molecules (drugs) cannot be patented, tested, and then licensed unless they can be shown to be novel to both patent examiners and regulators. However, not all drugs are breakthrough drugs—many merely fill gaps.

This study focuses on TBNFs located in the UK, where biotech is thriving and the two knowledge-development modes are prevalent. The UK leads Europe in biotech development and holds a significant place in the world (Owen-Smith, Riccaboni, Pammolli, and Powell, 2002). In the UK, there is plentiful data on TBNFs because of public disclosure laws (unlike the United States, where it is very difficult to obtain data on TBNFs that are not publicly listed because private firms are not required to disclose their financial and organizational characteristics). Despite its peculiarities, this context is economically and socially important in its own right, and it has features that are highly relevant to other contexts—it takes knowledge from well-established domains and develops new knowledge by a process of search, deep-dives, and recombination that produces results that clearly change the world.

All UK biotechnology firms founded between 1995 and 2005 were identified. The data were multi-sourced from directories of the UK Government DTI Bioscience unit; the United States Patent and Trademark Office (USPTO); the British Venture Capital Association; regional life sciences networking groups; and commercial databases such as BIO Century, VentureXpert, and FAME that are verified with the UK companies' registration office database at Companies House. In line with past research (Rothaermel and Deeds, 2004), this study focused on those companies that are involved in the research, development, and commercialization of human therapeutics that are placed in the human body (in vivo) and not those that are used outside the human body (in vitro therapeutics). This means the study excluded companies that were involved in other biotechnology application segments such as specialist product or service suppliers, diagnostics, tissue engineering, drug delivery, medical engineering, and agro-based biotechnology companies.

From this initial set of 120 companies, each firm's history was traced and we collected data for each year of observation from founding until 2005 or when the firm either ceased to exist or was acquired, whichever came first. Those firms that are subsidiaries of established firms or of foreign origin were excluded. After dropping companies because of lack of data, the final sample consisted of 69 firms.

Measures

Dependent variables. The first dependent variable measures the number of the firm's patents that turned out to be a breakthrough innovation in the three-year window by year t . It takes two steps to calculate this variable. First, the potential influence or importance of the firm's inventions in year t was measured. It is widely agreed in the literature that potential influence can be measured by the *net forward cites* of a firm's patents (e.g., Kaplan and Vakili, 2015; Phene et al., 2006; Trajtenberg, 1990). This was measured by first identifying a firm's original patents at year t and then computing for each patent the total number of forward citations (excluding self-citations) in the ten-year window from the date of application. Because the database ended in 2005, all patents had an equal ten-year window of observations.

In the second step, the total number of breakthrough innovations a firm has achieved in the three-year window by year t were identified and counted. Following previous writers (e.g., Kaplan and Vakili, 2015; Phene et al., 2006), the original patents of the whole dataset were sorted according to their number of net forward citations received and coded as a breakthrough if the patents in year t received the top 5% net forward citations. In robustness checks, breakthrough innovations for firms receiving the top 10% of all citations were computed in a similar way. Finally, the total number of breakthrough innovations in a three-year window were counted. Thus, the breakthrough innovation for any firm in year 2000, for instance, is the sum of the number of breakthrough innovations in the years between 1998 and 2000. The year window method is commonly adopted by prior studies that use patents to measure firm innovation outcomes, as it attenuates any annual fluctuations and thus captures a firm's patenting propensity more accurately (e.g., Ahuja, 2000; Rothaermel and Deeds, 2004; Zhang and Baden-Fuller, 2010). In our robustness checks, a four-year window was used.

The second dependent variable, *product development rate*, is a time-dated hazard rate for the firm's first product development milestone, phase I clinical trials. The hazard rate incorporates two pieces of information: first, whether the firm reached the product development milestone in year t , and second, the rate of development (i.e., the *time in months* it takes from the founding of the firm to its first product development milestone of clinical phase I). When a biotechnology firm's products in development have

successfully entered phase I clinical trials, it signals that the firm has effectively managed to generate and apply knowledge, a point that is widely acknowledged in this field (e.g., Rothaermel and Deeds, 2004). Many firms in this sector do not have commercial products for a long time, and this measure is thus appropriate as a measure of a key (albeit interim) milestone success (e.g., Rothaermel and Deeds, 2004). In addition, since the focus was on whether and when the firm is able to achieve the product development milestone for those firms that achieve breakthrough innovations, the sample was limited to those firms that have obtained at least one breakthrough innovation during the observed years and excluded firms without any breakthrough innovations.

Independent variables: Knowledge development mode. The firms' *knowledge development mode* was classified as either internally or externally focused. It is well documented that TBNFs in biotechnology often adopt an external mode of knowledge management (see, for instance, Luukkonen, 2005, on vertical disintegration in young Finnish biotech firms; Mangematin et al., 2003, on French biotech firms' knowledge trajectories; and Haagen, Haussler, Harhoff, Murray, and Rudolph, 2007, on the knowledge structures of young UK and German biotech firms). Following the logic of the argument, for each firm in year t , its knowledge management mode was classified as "internally focused" and set the value as "1" if the firm has a laboratory and "wet bench" scientists to cover upstream activities of the pharmaceutical value chain.² On the other end, the externally focused mode is coded as "0," which applies to virtual firms that do not have R&D facilities of their own, i.e., that have no "wet bench" scientists and rely on outsourcing for their R&D knowledge development activities (e.g., Cavalla, Flack, and Jennings, 1997; Chakma et al., 2009).

The data on whether a company had a laboratory was obtained from detailed financial reports of the firms (from Companies House), filing documents from

the stock exchange (for those firms listed on the stock exchange), press releases, and industry and company websites. While the coding was largely based on objective data, to ensure the reliability of the coding, five follow-up interviews were first conducted with the founders of firms to verify the nature of their knowledge approach and to confirm that the coding approach made sense. Then, two of the co-authors coded the variables separately, and the inter-rater reliability was 0.93—well above the conventional cut-off point (Cohen and Cohen, 1983). Finally, all three authors verified and agreed on the coding. As a result of the coding, 56 of the 69 firms were consistent in their knowledge approach throughout their lifetimes, and 13 switched. Of these 13, only 1 switched twice (external to internal and then back to external). The remaining firms switched only once, and the most common change was for a firm to start with the external mode, then to move to the internal mode.

Below, a few examples are provided to illustrate how firm knowledge-development modes were classified. The first, Arrow Therapeutics Limited, was one of the UK's premier small biotechnology firms and employed an internally focused knowledge development model. Arrow developed a fully kitted laboratory with core research capabilities in virology, microbiology, and chemistry under the firm hierarchy. At its peak, Arrow had 60 multidisciplinary R&D employees out of a total of approximately 80. Arrow's internal research capabilities were the primary driver of its innovation development strategy. In addition, Arrow had complementary alliances with academic and public research units, specialist providers, and large pharmaceutical companies. The second example is of a virtual and thus externally focused knowledge development model typified by Evolutec plc, a UK-based 1998 spin-off from a public research institution. Although Evolutec managed to raise funds comparable to Arrow, it had only approximately 11 employees, most of whom were considered administrative staff. Evolutec had no R&D facilities or any in-house "wet bench" scientists. Employees classified as R&D staff were project managers involved in coordinating the development of projects in their partner network. Another externally focused firm, Alizyme, mentioned earlier, had 19 employees, including 14 scientists, but (confirmed by interview) none of these scientists were involved as "wet bench" scientists, as there was no laboratory. The scientists' main duties included designing R&D studies in conjunction with partner scientists and monitoring R&D work undertaken by partners.

²The progression of drug discovery and development stages in biotechnology is well documented (e.g., Giovannetti and Morrison, 2000; Smith, 2004; Rothaermel and Deeds, 2004). The first stage is target identification, which largely involves molecular biology and genomics. The next stage is lead discovery, which is an iterative process involving chemistry and biochemistry and then a lead optimization process that involves technologies such as high throughput screening and combinatorial chemistry. This stage is followed by pharmaceutical development, which involves a preclinical phase and three clinical phases of development that look at the toxicological characteristics and involve pharmacology, chemical development, pharmaceuticals, volunteer studies, etc. Although this listing is not meant to be exhaustive, it underlies the fact that the process is multidisciplinary, sequential, and systemic, i.e., there are feedback loops between the distinct activities.

Controls. Past research has highlighted the importance of several control variables that may impact successful firm innovation. Except where indicated, all controls were time varying.

The most important control is money raised by the firm, which we expect to have a positive influence on innovation outcomes. The variable *funds* measures the cumulative amount of funds raised since the firm's founding by year t , measured in £ sterling. This measure indicates the amount of funds the firm is able to commit to R&D programs both inside and outside the firm's boundaries, and it signals capacity to innovate (e.g., Sørensen and Stuart, 2000). The natural logarithm of funds was used in data analysis due to the skewed distribution of the variable.

VC backing is included to capture whether a firm was financed by venture capital firms (VCs) in any particular year, expecting this control to be positively related to innovation outcomes (e.g., Rothaermel and Deeds, 2004). Approximately 60% of our sample had such backing. VCs, as specialist investors attempting to achieve consistently high returns, can have a substantial influence on a TBNF's knowledge building trajectory and strategy and can encourage focus and effective outcomes through the execution of a fast growth strategy (Haagen et al., 2007).

A binary variable, *listing*, was included that takes the value 1 if a firm was listed on a public stock exchange in year t . Public exchanges are a real alternative for funding small firms that may not want to go the VC route (e.g., Rothaermel and Deeds, 2004). Only a small number of sample firms achieved listing during the time of our research. Public listing could positively influence a firm's attitude toward breakthrough innovation (see, for instance, Owen and Hopkins, 2016).

The total number of *employees* was used as a proxy for firm size. Past researchers in the biotech field make the point that larger firms are more likely to be effective at innovation. Although firm size is often measured in revenues or market share, most biotech firms do not have significant revenue streams in their early stages, thus making the measure inappropriate in this sector (Shan, Walker, and Kogut, 1994). We use the natural logarithm of employees in data analysis because of the skewed distribution of the variable.

The number of *alliances* the firm is involved in at year t are used as a control. Alliances are a key source of resources for the focal firm, and many researchers argue that alliances improve innovative performance (e.g., Baum, Calabrese, and Silverman, 2000).

A time invariant dummy, *technology type*, was included to indicate whether a firm's technology is based on small molecule technology or any other type, such as large molecule biologics. This measure was used to control for the fact that different technologies may have different levels of difficulty that may affect innovative outcomes.

Finally, *therapeutic categories* were included, measured by the number of customer segments in which the company has active research projects. The information is reported in Bio Century (e.g., Hoang and Rothaermel, 2010). The measure denotes a firm's participation in different product-market applications. A biotech firm can be involved in multiproduct innovation projects whereby each project is classified in terms of a major therapeutic area that is perhaps more likely to produce breakthrough innovations (but subject to a given level of funding, size, and other control factors) but is less likely to produce a good product-development rate. A given level of the TBNF's resources is spread over more projects (e.g., Hoang and Rothaermel, 2010). Table 1 summarizes the variables and their measurements.

Estimation Procedure

The dataset is an unbalanced 11-year panel consisting of 370 firm-year observations for the 69 firms in our sample. As noted before, only 13 of the 69 firms have ever changed the knowledge development mode during the 11 years, among which 12 firms only changed once. Therefore, random-effects models were used in the data analysis. This is because the aim is not to understand why a firm might switch its knowledge mode but rather what are the effects of the mode. Fixed-effects models should be applied only when the research seeks to analyze the impact of variables that vary over time (Baltagi, 2008).

To test H1, negative binomial regressions were modeled because the dependent variable is the count of breakthrough innovations, and its distribution is skewed (Phene et al., 2006). To test H2, where the dependent variable combines the probability of and the time to an event, i.e., the first key product development milestone, Cox propositional hazard models were employed to perform the event history analysis (e.g., Cox, 1972). The results of Cox models can be interpreted as follows: "a positive (negative) coefficient sign would indicate a greater (lower) hazard of the focal event occurring. Hence, the variable of interest

Table 1. Measurement of the Variables

Variable	Measurement	Time varies for each firm
Breakthrough invention	Number of breakthrough patents in 3-year window by year <i>t</i> . Breakthrough patents are defined as the top 5% patents ranked by total net patent citations each patent received in a 10-year window from application date. Robustness checks use the top 2% and 10% definitions and a 4-year window.	Yes
Product development rate	Dummy variable that takes a value of 1 if and when a firm first announces a product is in clinical phase I trials	Yes
Time (month)	The number of months when a product reaches the clinical phase I trials	Yes
Knowledge development mode	Dummy that takes a value of 1 for internal mode, that is, if the firm has a laboratory and employs “wet bench scientists” and zero for the external mode	Rarely ^a
Listing	Dummy variable that takes a value of 1 if and when the firm is publicly listed	Rarely ^b
VC backing	Dummy variable that takes a value of 1 if and when the firm is venture capital backed and zero otherwise	Rarely ^b
Ln (funds)	Cumulative funds raised by firm in any given year	Yes
Ln (employees)	Total number of employees in firm	Yes
Alliances	Number of alliances announced by firm in year	Yes
Therapeutic categories	Number of therapeutic categories the firm is reported to engage in as reported by Bio Century	No
Technology type	Dummy variable that takes a value of 1 if the firm R&D program involves small molecules and zero otherwise	No

^a56 of the 69 firms were consistent in their knowledge approach throughout their lifetimes, and 13 switched. Of these 13, only 1 switched twice (external to internal and then back to external). The remaining firms switched only once.

^bA firm’s listing or VC backing status will take the value “0” until it went public or received VC funds. After that, the status will take the value “1.”

leads to a faster (slower) occurrence of the focal event. Higher (lower) hazard rates, in turn, suggest a larger (smaller) number of such events within a given time period” (Hoang and Rothaermel, 2010, p. 745).

Results

Descriptive Analysis

Table 2 provides the descriptive statistics and the correlations between variables. To check for potential problems with collinearity, the variance inflation factors (VIFs) were estimated, and they were well below

the recommended limit of 10 (e.g., Stevens, 1992). The relationships between these variables will be examined more thoroughly in the regression model analysis that follows.

The average age of the sample firms was approximately 5 years, and they had raised an average of approximately £13 million. Just over 50% of these firms had the internally focused knowledge development mode, and most obtained funding from VCs. On average, all sample firms sourced knowledge from approximately seven external partners, participated in two therapeutic categories, employed 25 employees, and were granted approximately three to four patents.

Table 2. Descriptive Statistics and Bivariate Correlation Matrix

	Mean	S.D.	Min	Max	1	2	3	4	5	6	7	8	9	10
1 Breakthrough innovation	0.19	0.39	0	1	1.00									
2 Knowledge develop. mode	0.61	0.49	0	1	0.15	1.00								
3 Product development rate	0.23	0.42	0	1	0.18	0.09	1.00							
4 Time (months)	47.93	27.95	1	129	0.27	0.24	0.49	1.00						
5 Listing	0.08	0.27	0	1	0.32	-0.04	0.35	0.31	1.00					
6 VC backing	0.63	0.48	0	1	0.00	0.12	0.01	0.12	-0.14	1.00				
7 Ln (funds)	1.54	1.78	-3.00	4.45	0.34	0.50	0.48	0.62	0.26	0.24	1.00			
8 Ln (employees)	2.34	1.25	0	4.70	0.29	0.71	0.37	0.53	0.14	0.11	0.80	1.00		
9 Alliances	1.32	2.47	0	41	-0.09	-0.01	-0.09	-0.09	0.03	0.03	-0.01	0.04	1.00	
10 Therapeutic categories	1.95	0.99	1	5	-0.11	-0.10	0.06	0.04	0.09	-0.01	0.15	0.04	0.13	1.00
11 Technology type	0.66	0.47	0	1	0.04	0.05	0.04	0.05	0.14	0.12	0.22	0.14	0.07	0.13

p < .05 when coefficient is larger than 0.10.

Table 3. Effects of the Knowledge-Development Modes on the Number of Breakthrough Innovation (H1)

	Breakthrough (5% and 3-year window)			Breakthrough (5% and 4-year window)	Breakthrough (10% and 3-year window)
	Model 1	Model 2	Model 3	Model 4	Model 5
Listing	1.097** (0.487)	0.937 (0.555)	1.062* (0.448)	1.135*** (0.352)	0.500 (0.307)
VC backing	0.959** (0.480)	1.034** (0.474)	0.804 (0.406)*	1.075*** (0.361)	−0.143 (0.270)
Ln (funds)	0.938*** (0.226)	0.828*** (0.222)		0.824*** (0.196)	0.299 (0.174)
Ln (employees)	0.237 (0.170)	0.533*** (0.206)	1.149** (0.202)	0.520*** (0.193)	0.577** (0.225)
Alliances	−0.138 (0.085)	−0.156 (0.089)	−0.200* (0.096)	−0.189** (0.087)	−0.204** (0.090)
Therapeutic categories	−0.294 (0.173)	−0.346 (0.188)	−0.301 (0.178)	−0.316 (0.161)	−0.192 (0.112)
Technology type	0.389 (0.354)	0.353 (0.356)	0.269 (0.317)	0.418 (0.298)	0.109 (0.267)
Knowledge development mode (external=0; internal=1)		−0.784* (0.459)	−1.147** (0.484)	−0.596* (0.369)	−0.553* (0.308)
Year dummies	Included	Included	Included	Included	Included
Constant	−16.083	−16.928	−18.277	−13.212	−14.487
N	373	373	391	373	373
Log pseudo likelihood	−114.69	−113.68	−131.35	−142.47	−208.11
Pseudo R ²	0.3558	0.3614	0.3022	0.3491	0.2103

Coefficients are reported, and standard errors are in parentheses.

*** $p < .01$, ** $p < .05$, * $p < .1$.

These results are comparable to those obtained in other management studies in the biotech sector (Mangematin et al., 2003; Rothaermel and Deeds, 2004).

Hypotheses tests. Tables 3 and 4 report the results of testing H1 and H2, respectively. H1 predicts that the external knowledge mode is associated with more breakthrough innovation. A negative binomial regression is employed. Model 1 in Table 3 is the baseline model with all control variables, and the variable *knowledge development mode* is introduced in model 2. The results in model 2 show that the firms with the externally focused knowledge-development mode are associated with more breakthrough innovation outputs ($b = -0.784$, $p < .10$). The effect size of the knowledge development mode was calculated. The result suggests that the internal mode is associated with 45.7% as many breakthrough innovations as the external mode, i.e., is 54.3% less productive, holding all other variables in the model constant. Overall, H1 is supported.

H2 suggests that, compared to those with the internally focused knowledge development mode, firms with the external mode will be associated with a higher rate of achieving the milestone that the first

product goes under development in phase I clinical trials; and the sample is restricted to those firms that achieve a breakthrough innovation. To test this hypothesis, Cox propositional hazards models were applied. Model 2 in Table 4 shows that the firms with the internal mode are significantly and negatively associated with achieving the product development milestone ($b = -3.854$, $p < .05$). Again, the effect size of the knowledge-development mode was checked. Using a 95% confidence interval, the lower bound hazard ratio is 0.129 for the variable, which suggests that adopting the externally focused knowledge-development mode will increase the probability of achieving the product innovation milestone and that a firm that has not yet achieved a milestone by a certain time has at least 7.7 times ($=1/0.129$) more chance to achieve a milestone at the next point in time compared to firms with an internally focused mode. All results lend support to H2.

Robustness checks. A number of robustness tests on H1 were conducted. First, the effect of eliminating $\ln(\text{funds})$ in the data analysis was examined, since this control variable is highly correlated with another control variable $\ln(\text{employees})$ ($b = 0.80$). Second, a four-

Table 4. Effects of the Knowledge-Development Modes on the Hazard Rate of Reaching the First Product Development Milestone (H2)

	Breakthrough (5%)			Breakthrough (10%) Model 4
	Model 1	Model 2	Model 3	
Listing	1.152 (1.275)	0.0639 (1.454)	-0.655 (1.321)	0.700 (1.389)
VC backing	0.699 (1.563)	0.685 (1.965)	-1.037 (2.303)	1.630 (1.506)
Ln (funds)	-0.882 (0.765)	-1.681* (0.953)		-1.786** (0.890)
Ln (employees)	0.0705 (0.451)	2.057 (1.318)	0.993 (0.827)	1.910 (1.228)
Alliances	-0.121 (0.369)	-0.123 (0.368)	-0.191 (0.371)	-0.113 (0.364)
Therapeutic categories	-0.737 (0.848)	-0.656 (1.002)	-1.269 (1.437)	-0.406 (0.702)
Technology type	1.192 (1.235)	1.449 (1.749)	0.712 (1.396)	1.181 (1.561)
Knowledge development mode (external=0; internal=1)		-3.854** (1.808)	-2.916* (1.536)	-3.550** (1.800)
N	71	71	76	77
chi-square	4.747	11.20	8.303	13.60
df	7	8	7	8
Log likelihood	-23.03	-19.81	-21.54	-22.12
Pseudo R ²	0.0934	0.220	0.162	0.235

Coefficients are reported, and standard errors are in parentheses.

** $p < .05$, * $p < .1$.

year window was adopted to replace the three-year window when counting the number of breakthrough innovations. Third, the top 5% of patent citations were substituted by 10% when defining a breakthrough innovation. The effect of the knowledge mode variable remained, as shown in Table 3 Models 3–5 respectively. Hence, the result on the H1 test is robust to a satisfactory level.

A number of robustness tests on H2 were also conducted. For similar reasons as above, ln(fund) in the model was first excluded. Then, the top 5% of patent citations were substituted by 10% when defining breakthrough innovation. The effect of the knowledge mode variable remained, as shown in Table 4 Models 3–4. Hence, the result on the H2 test is robust to a satisfactory level.

Additional tests related to the hypotheses were conducted. First, using Cox models, the external mode was tested for its association with a higher rate of breakthrough innovation. The hypothesis is supported, but only for the first breakthrough innovation ($b = -1.44, p < .05$). The finding is consistent with and adds to the original findings in testing H1. Second, H2 was tested using Probit models instead of Cox models. Again, the result remained ($b = -1.92, p < .05$). This suggests that the external mode will give firms a higher chance of reaching the

milestone of product innovation, which is consistent with and adds to the original finding in testing H2.

Endogeneity is a potential concern in this study because the firm’s choice of knowledge development mode may be influenced by some variables that also affect firm innovation outcomes. Most of the obvious variables that may cause endogeneity were controlled for, such as firm funds, employee size, number of alliance partners, and type of technologies. The potential endogeneity issue caused by missing variables is further minimized with a panel data set (Semykina and Wooldridge, 2010). The knowledge development mode represents a managerial attitude to knowledge development that occurs before founding and is not often changed. The interviews carried out as part of this study suggested that such changes occur when a firm hits a crisis and needs a fundamental change of direction. These issues are touched on in more detail in the next section.

Discussion

In answer to the call that authors should study the coordination mechanisms, models, and approaches that

are most effective at producing breakthrough innovations, this study identified two different firm knowledge development modes used by technology-based new firms (TBNFs): internally versus externally focused knowledge development. These two modes are organized differently to meet the prerequisites for achieving a breakthrough, i.e., assembling distant and diverse knowledge and undertaking deep-dives (Kaplan and Vakili, 2015; Phene et al., 2006). The approaches differ in loci of creativity, how they organize knowledge assembly and subsequent development, and how they deal with path dependence. For the internal mode, the locus of creativity is inside the firm, and knowledge assembly often requires moving knowledge from outside the firm to inside and developing it internally. This mode is associated with a strong onset of path-dependence. In contrast, with the external mode, the locus of creativity is in the network, and knowledge assembly does not require knowledge transfer—to the contrary, almost all development is by partners. This frees the firm from strong path-dependence tendencies. And in terms of resources, the external mode is far more flexible, because it utilizes the resources of others rather than assembling its own.

The two modes of knowledge development, as explained in the paper, are essentially mutually exclusive when applied to small firms. The setting of TBNFs in the highly creative UK biotechnology drug industry is used to show how these two development modes mapped onto the likelihood of breakthrough innovations and subsequent product development. Even though the total population of TBNFs is small in this setting, there appears to be strong evidence that the external mode was associated with more breakthrough innovations and speedier development of products to market. The statistical analysis suggests that firms with an external mode are more productive in achieving breakthrough innovations compared to firms with an internal mode. In addition, adopting the external mode will speed up the process of achieving the subsequent product innovation milestone.

For the internal mode, the creative tension necessary for breakthrough innovation rests primarily on in-house multi-disciplinary R&D teams with gaps being filled through alliances. However, the relatively quicker onset of path dependence is tempered somewhat with the ability of the internal mode to achieve the requisite variation necessary for greater breakthrough productivity, at least relative to the external mode, which on balance proves to be more adept because of its flexible access to knowledge.

Additionally, the difficulty of assembling multi-disciplinary in-house capabilities and building alliances simultaneously proves to be a relatively greater challenge that impedes progress for an internal mode firm (e.g., Sapienza et al., 2006).

The results also show that the external mode is not necessarily impeded by its inability to undertake deep-dives—an obvious advantage the internal mode has. By playing an integrative role in a network of partners that provide specialist services limited to specific parts of a value chain, the external mode is able to tap into and access external knowledge. Sufficient motivation for partners can be mustered, ranging from financial, i.e., providing services for a fee, to strategic, where partners view their involvement as an option on developing new technology that may be of future value. The external mode as a focal firm plays a key integral role that is responsible for the vision, building, developing, and managing of the network. Additionally, partners find value in the ability of the focal firm to share knowledge from across the network or as a profitable use of knowledge that they already have but is not fully utilized.

Theoretical Implications

This study offers important theoretical implications regarding the understanding of how TBNFs organize for breakthrough innovation. First, as emphasized in the special issue call, the innovation literature generally considers start-ups as the natural engines of breakthroughs because of their creativity and lack of organizational inertia. This study shows that the loci of creativity in start-ups is actually varied and is linked to how the firm is organized. The loci of creativity can either be firmly within the firm or in its network, depending on the organizing approach. Moreover, the approaches have different underlying assumptions and models, particularly the learning approach in the alliances formed (e.g., Grant and Baden-Fuller, 2004; Hoang and Rothaermel, 2005, 2010). More specifically, each mode is associated with a different approach by which firms can identify distant knowledge, organize subsequent deep-dives into the assembled knowledge, and arrange the subsequent codification and exploitation of that knowledge to yield potentially breakthrough results (e.g., Brusoni, Prencipe, and Pavitt, 2001; Padgett and Powell, 2003; Powell et al., 1996; Prencipe, 1997; Rothaermel and Deeds, 2004).

This study extends innovation literature that has hitherto focused on highlighting specific ways in which firms involve external actors in developing their knowledge to foster innovations (e.g., Chesbrough, 2003, 2006). For example, Fey and Birkinshaw (2005) examine R&D collaborations generally, whereas Grimpe and Kaiser (2010) and Laursen and Salter (2006) look specifically at the role of in-licensing and acquisition of R&D services. This paper's contribution is uniquely about the different ways in which networks are used by start-ups. In the internal mode, networks are used to either spur internal efforts and to fill gaps, whereas in the external mode, networks are used for both exploration and exploitation. There is a parallel between the external development mode and the way individual scientists (or small groups of scientists) increasingly use collaborations embedded in networks. Stephan (2012) notes that investigators that have a greater external focus can move away from safe, easily fundable projects to less easily fundable ones but with uncertain but potentially path-breaking outcomes. Whilst it may be difficult to infer organizational principles discussed at the level of the firm to those for individuals or small groups of investigators, both can benefit from the same principles.

Second, there is need to re-evaluate the traditional literature concerning the connection between absorptive capacity and innovation. Absorptive capacity is normally associated with the firm's ability to form effective alliances, absorb knowledge from outside the firm, and subsequently produce innovations internally (e.g., Cohen and Levinthal, 1990; Kaplan and Vakili, 2015; Phene et al., 2006). This work suggests that a TBNF can take an external approach and can utilize the search capabilities and absorptive capacity of partners when undertaking fundamental research and that it is partners that can undertake the deep-dives associated with breakthrough (Weisberg, 1999). External development approaches do not contradict traditional notions—they reflect how they may be stretched to emphasize different innovation outcomes. This is a topic ripe for further research.

Third, this study suggests that choosing between different knowledge-development modes is, in effect, a choice between different risk paths and approaches to option building (McGrath and MacMillan, 2000). External knowledge modes seem to be less shackled by path dependence and use their inherent flexibility to source knowledge more widely (e.g., Schilling and Steensma, 2001) and at the same time use partners to

achieve necessary deep-dives. This means that innovation outcomes for the external mode are more likely to be breakthrough and reach the market more speedily. Seeing these two paths as a choice between mean-enhancing innovations versus those that encourage variance-enhancing outcomes (in particular breakthroughs) also goes some way towards answering the questions raised by Carayannopoulos and Auster (2010) and Taylor and Greve (2006). Also, hints are given of how traditional concerns of agency costs in the external mode may arise from opportunism or lack of control (Chesbrough and Teece, 1996) can be overcome. Careful strategies to mitigate these risks include disclosure strategies (Katila et al., 2008) or the right incentives (Owen-Smith et al., 2002; Powell et al., 1996).

Fourth, this study contributes to the emerging literature on business models that labels different activity systems and governance arrangements between the firm and external actors as different business models (see, for instance, Amit and Zott, 2001; Zott and Amit, 2010). Past empirical work has only looked at the effect of different business model arrangements on profitability outcomes, whereas this study extends the work to breakthrough innovation. Moreover, this investigation suggests that these business model types can be tied up to different sets of managerial processes, in line with emergent thinking about business models as cognitive types (see, for instance, Baden-Fuller and Haefliger, 2013; Baden-Fuller and Morgan, 2010).

Managerial implications. This study sheds light on a current challenge of the biotechnology industry, with important implications for policy makers and managers about the value of small firm–large firm (and public–private) collaborations that are central in the networks of the externally organized firms. Recent reviews have noted that there has been a relative dearth of breakthroughs in biotech for the level of investment that has been poured into the sector (Owen and Hopkins, 2016; Pisano, 2006). Pisano, in particular, highlights the challenges faced by conventional organizations. This research suggests that the external knowledge mode, as an organizational arrangement, may be a way forward. It achieves a different (and arguably better) balance between the tension of searching widely for external and distant knowledge (Kaplan and Vakili, 2015) and the capacity to undertake deep-dives (Weisberg, 1999), two prerequisites that have been highlighted in the innovation literature as necessary for achieving breakthroughs.

This research also hints that the external mode may also be resource efficient. This suggests that managers of TBNFs should seriously consider the external mode if they value speedy product development that exploits breakthrough innovations. However, something that was not investigated in this paper is that the long-term effectiveness of the external mode depends on the availability of external partners. The interviews in this study suggested that government-sponsored laboratories that operate either within universities or are located within big charities, such as Wellcome Trust, are important potential partners. This means that public policy has a potentially important role in fostering external knowledge development, with potentially important social benefits. To be more certain, a wider research project is needed that looks at innovation performance across both large and small firms and incorporates the role of public laboratories in multiple contexts to fully understand the determinants of breakthrough innovations and the barriers to their exploitation (Narin, Kimberly, and Olivastro, 1997).

Limitations and Future Research

One of the major limitations of this study is that the antecedents to the knowledge development mode choices were not explored, which is constrained by the scope of our study. Indeed interviews in this study suggest that the choice of the modes reflect a difference in orientation of founders, but this leaves open the question of how these orientations come about. Future studies will need to model the firms' choice of knowledge development modes directly. As mentioned before, endogeneity is a potential concern because the firm's choice of knowledge development mode might be influenced by variables that also affect firm innovation outcomes. Endogeneity concerns were minimized by controlling for most of the obvious variables that may cause endogeneity and by using a panel data set. A future study on the antecedents to the knowledge development mode choice is the only way to truly unpack the endogeneity concern and obtain more robust conclusions.

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