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How Central Is Too Central? Organizing Interorganizational Collaboration Networks for Breakthrough Innovation

John Qi Dong, Killian J. McCarthy , and Wilfred W. M. E. Schoenmakers

Firms increasingly look to collaboration with alliance partners in their quest for breakthrough innovation. But how does the position of a firm in its alliance network weighted by the centrality of its partners—a concept which we term “partner-weighted alliance centrality”—and the heterogeneities in the types of partners that it cooperates with—in terms of its private-public collaboration—influence this quest? Using longitudinal data from the U.S. pharmaceutical industry, we build alliance networks in the period 1985–2001 to investigate these questions. We show that, for breakthrough innovation, collaborating with more partners that are more central in alliance networks the better, but only to a point. Beyond that point, we find that the likelihood of achieving breakthrough innovation drops. Furthermore, and looking at the kinds of knowledge provided by the partners in each firm’s alliances, we report that firms with a greater share of private partners, relative to public partners, suffer less from the diminishing benefits of collaboration with central partners when developing breakthrough innovation. Taken together, we make novel contributions about how to organize for breakthrough innovation, and provide actionable managerial advice in terms of selecting collaborative partners in alliance networks.

Practitioner Points

- Managers can manage the development of breakthrough innovation by carefully selecting collaborative partners in alliance networks.
- Firms that partner with central partners can develop more breakthrough innovations with diverse knowledge, while more central partners can also push the limits of the firms’ ability to understand and to use highly diverse knowledge.
- The types of partners matter for developing breakthrough innovation, and that having a greater share of private partnerships allows the firms to overcome the limits.

Introduction

There are many types of innovation (Garcia and Calantone, 2002; Schoenmakers and Duysters, 2010). “Breakthrough” innovation remains, however, the holy grail (Verganti, 2008).

A breakthrough innovation is a “game-changing” (O’Connor and De Martino, 2006), “foundational” invention (Ahuja and Lampert, 2001), which can cause paradigm shifts in technological trajectories, and can lead to the creation of new customers and new markets (Ahuja and Lampert, 2001; Dahlin and Behrens, 2005; Tellis, Prabhu, and Chandy, 2009). Firms invest in the development of breakthrough innovation because research shows that those that develop breakthrough innovation tend to perform better and to survive longer (Abernathy and Utterback, 1978; Cooper and Schendel, 1976; Henderson and Clark, 1990; Hill and Rothaermel, 2003; Rosenbloom and Christensen, 1998; Tushman and Anderson, 1986).

Firms, however, find it difficult to internally develop breakthrough innovation (Christensen, 1997; Henderson, 1993). Because innovation comes from recombining new knowledge inputs (Fleming, 2001; Wang, Choi, Wan, and Dong, 2016), many firms, aspiring to develop breakthrough innovation, therefore, look to strategic alliances as a way of finding new external knowledge (Dong and Yang, 2015; Faems, Van Looy, and Debackere, 2005). Strategic alliances are formal arrangements, between otherwise independent organizations, in which firms pool their technological resources (Faems, De Visser, Andries, and Van Looy, 2010) and by making alliances, firms aim to satisfy more of the conditions known to be necessary for

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the development of breakthrough innovation, such as access to new knowledge, exposure to emergent technologies, and an exposure to a large number of knowledge domains (Schoenmakers and Duysters, 2010). The majority of the research on alliances supports this suggestion, and shows that firms that engage in alliances tend to be more innovative (Deeds and Hill, 1996; Kotabe and Swan, 1995; Montoya-Weiss and Calantone, 1994; Shan, Walker, and Kogut, 1994). De Man and Duysters (2005) report that 73% of alliance studies find that alliances positively impact innovation.¹

Recent alliance literature suggests, however, that, rather than discrete arrangements, alliances should be understood as building blocks of interorganizational collaboration networks (e.g., Fernald, Pennings, and Claasen, 2014; Gilsing and Nooteboom, 2006; Gilsing, Nooteboom, Vanhaverbeke, Duysters, and van den Oord, 2008; Powell, Koput, and Smith-Doerr, 1996; Vanhaverbeke, Gilsing, and Duysters, 2012).² Social network research shows that the more

central an organization is in the network, the greater the information and knowledge that it is able to reap from the network (Kilduff and Brass, 2010). The suggestion is that, because breakthrough innovation requires a diversity of knowledge inputs (Schoenmakers and Duysters, 2010), firms that collaborate with other central organizations, in order to get access to more and more diverse external knowledge, will be more successful. Successful innovators, in other words, will not only tend to form alliances, but will tend to be central in their alliance networks by collaborating with other central organizations.

Alliance network centrality may not, however, always be beneficial for breakthrough innovation. Indeed, Gilsing et al. (2008) demonstrate an inverted U-shaped relationship between a firm's alliance network centrality and its search for knowledge that is new to the firm.³ Firms with central partners in an alliance network, we argue, will be exposed to more and more diverse knowledge (Gnyawali and Madhavan, 2001), which increases the chance of developing breakthrough innovation (Fleming, 2001; Schoenmakers and Duysters, 2010). At the same time, the absorptive capacity literature (Cohen and Levinthal, 1990; Zahra and George, 2002), warns that not all external knowledge can be fully absorbed, and that a high diversity of knowledge not only increases the complexity of knowledge recombination, but can lead to a random drift in the firm's knowledge base too. Because both the benefits and drawbacks of alliance network centrality increase not only with a firm's number of partners, but also with the degree to which the firm collaborates with other central organizations, we theorize an inverted U-shaped relationship between a firm's position in the alliance network weighted by its partners' centrality—a concept which we term “partner-weighted alliance centrality”—and breakthrough innovation.

We then extend our theorizing to consider the types of partners in a firm's alliances. We argue that, because private and public partners⁴ own different kinds of knowledge (Gulbrandsen, Mowery, and Feldman, 2011), and present different opportunities and challenges for developing breakthrough innovation, firms may look to enrich their collaboration, by adding public partners, such as universities and government-funded institutions, to their alliance networks. We argue

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¹Of the remainder, 17% have a neutral impact, and 10% have a negative impact on innovation.

²When Firm A and B, for example, make an alliance, they add to the pre-existing alliances between Firm A and C, and between Firm B and D, and enhance the network between all four.

³Gilsing et al. (2008) use betweenness centrality to measure the way in which knowledge flows across the firm, to explain exploration, which is the search for knowledge that is new to the firm.

⁴In this study, private partners include firms in private sectors, whereas public partners include universities or government-funded institutions in the public sectors. While some universities are likely to be privately owned, they are close to publicly owned universities in terms of their missions, activities, and the kinds of knowledge in particular. Therefore, we group them into public partners.

that the share of private-public partners is likely to moderate the inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation, but in a nuanced manner. However, we suggest that a greater share of public partners relative to private partners in a firm's alliances will increase the diversity of knowledge inputs from the alliance network (Gesing, Antons, Piening, Rese, and Salge, 2015; Knudsen, 2007), indicating that firms with more public partners than private partners will reap more of the benefits of partner-weighted centrality for developing breakthrough innovation. However, we argue that a higher share of private partners relative to public partners in a firm's alliances facilitates the assimilation and recombination of knowledge inputs due to the similarity of knowledge base (Cohen and Levinthal, 1990; Todorova and Durisin, 2007). Thus, we argue that firms with a larger share of private relative to public partners can better alleviate the problems of absorptive capacity that arise with increasing partner-weighted alliance centrality.

We test our hypotheses using a panel data set from the U.S. pharmaceutical industry, over a 15-year period, from 1985 to 2001, and we find largely supportive evidence.

In doing so, we contribute to the breakthrough innovation literature by investigating: (1) to what extent the position of the firm in interorganizational collaboration networks—in terms of partner-weighted centrality—leads to the development of breakthrough innovation; and (2) under what conditions—in terms of partner heterogeneity in private-public collaboration—this impact may vary. We show, first, that by managing its centrality, by selecting partners that are not very central or peripheral in the alliance network, a firm can reduce the problems of absorbing external knowledge while promoting breakthrough innovation. Second, we show that by choosing to partner with more private partners, relative to public partners, firms can alleviate the problems associated with absorbing external knowledge and enabling the discovery of breakthrough innovation. By doing so, and by demonstrating the impact of partner-weighted alliance centrality, and its interplay with private-public partner heterogeneity, on breakthrough innovation, we provide academics with a springboard for additional research on breakthrough innovation, and we provide managers with a number of actionable implications for stimulating breakthrough innovation.

Alliances as Interorganizational Collaboration Networks: Defining Partner-Weighted Alliance Centrality

Alliances are not discrete arrangements; firms possess a portfolio of interlinked alliances (Wassmer, 2010), which together form an alliance network (Gilsing and Nooteboom, 2006; Gilsing et al., 2008; Powell et al., 1996; Vanhaverbeke et al., 2012). This is defined as the “focal firm's egocentric network (i.e., all of its direct ties with partner firms; Baum, Calabrese, and Silverman, 2000; Ozcan and Eisenhardt, 2009; Wassmer, 2010)” (Fernald et al., 2014, p. 5).

Increasingly, alliance scholars suggest that the benefits of an alliance network are not shared evenly. In fact, research has suggested that the more central an organization is in a network, the greater advantage it can appropriate from the network. This fact has been demonstrated in a variety of contexts. Ahuja, Galletta, and Carley (2003) and Cross and Cummings (2004), for example, show that an individual's network centrality explains the performance in knowledge-intensive R&D work; Tsai (2001) and Durmusoglu (2013) show that a team's/business unit's network centrality explains its innovation performance; Powell et al. (1996), Gilsing et al. (2008) and Dong and Yang (2016) show that a firm's network centrality also explains its innovation performance. In sum, the research shows that firms collaborate for innovation, and that alliance network centrality matters for innovation.

There are, however, a number of different approaches to the conceptualization and operationalization of network centrality (Dong and Yang, 2016). Figure 1 provides an illustration of the most commonly used measures to capture alliance network centrality. The simplest, degree centrality, considers the number of ties of the focal firm, compared to the size of the network (Freeman, 1979). It is useful for considering how networked the firm is, in terms of the number of ties that it has, but it ignores potential heterogeneities in ties; all partners are assumed to be of equal significance, and because of this degree centrality may oversimplify the impact of a firm's alliance network centrality on innovation.

Betweenness centrality captures the number of times a focal firm is included on the shortest path between other organizations in the network (Freeman, 1979). It is useful for considering the “boundary-spanning” role of a firm, and as a result it is suitable for studies aiming to capture the degree to which a

Figure 1. An Illustration of Network Centrality

firm can bridge knowledge flows among other firms (e.g., Gilsing et al., 2008). Betweenness centrality, however, does not account for the significance of the focal firm's partners, as it again assumes that all partners are of equal significance, and thus, as a measure, betweenness centrality suffers from many of the same issues as degree centrality when deployed to study alliance network centrality.

Eigenvector centrality is a more sophisticated measure of the firm's alliance network centrality. It provides a partner-weighted measure of alliance network centrality, which we define as "the degree to which a firm collaborates with other central organizations in the alliance network." Partner-weighted alliance centrality not only takes the number of ties into account, but the differences in ties too. In other words, it gives more "weight" to the ties with central partners, and less "weight" to the ties with peripheral partners. To do so is important, we argue, because both the benefits and drawbacks of alliance network centrality increase not only in a firm's number of partners, but also in the degree to which the firm collaborates with other central organizations. Unlike degree centrality, partner-weighted alliance centrality is measured as the sum of centralities of a focal firm's partners in the alliance network, which indicates the centrality of a firm in terms of the centralities of its partners. Additionally, partner-weighted alliance centrality captures the network position of a focal firm with respect to its access to other organization's knowledge, rather than the network position regarding how it transfers another organization's knowledge, as is the case of betweenness centrality.

Hypotheses

The Curvilinear Effect of Partner-Weighted Alliance Centrality

We theorize an inverted U-shaped relationship—based on a positive and a negative latent mechanism—between partner-weighted alliance centrality and breakthrough innovation. We explain both mechanisms below. With respect to the *positive latent mechanism*, we argue that partner-weighted alliance centrality will benefit the development of breakthrough innovation. Firms collaborating with other central organizations in an alliance network will, we suggest, not only be exposed to more knowledge, but also to more diverse knowledge too (Gnyawali and Madhavan, 2001). This is because their central partners can get access to, and thereby provide them, more and diverse knowledge from the network (Kilduff and Brass, 2010). More and more diverse knowledge inputs associated with a high partner-weighted alliance centrality increases the potential of developing a breakthrough innovation (Fleming, 2001), because breakthrough innovation often occurs when bridging a large number of different knowledge domains (Schoenmakers and Duysters, 2010). In other words, we suggest that partner-weighted alliance centrality contributes to a firm's knowledge inputs, in terms of scale and diversity, and so partner-weighted alliance centrality increases the chance of developing breakthrough innovation. When partner-weighted alliance centrality increases, the increase in the scale and diversity of knowledge is expected to be proportional, or there is not a theoretical reason to believe unproportional change. Thus, the positive latent mechanism is likely to be a linear one.

Prior research suggests that the extent to which a firm is able to leverage its partners' knowledge depends on its absorptive capacity (Cohen and Levinthal, 1990), of which it has two types: potential and realized absorptive capacity. The former is essential to acquire and to assimilate external knowledge, while the latter is required to transform and to exploit assimilated knowledge (Zahra and George, 2002). Drawing on the absorptive capacity literature (Cohen and Levinthal, 1990; Zahra and George, 2002), we suggest a *negative latent mechanism*—which implies that the benefits and drawbacks of partner-weighted alliance centrality do not increase proportionately—for two reasons.

First, not all the external knowledge can be fully absorbed by a firm. With more and more diverse

knowledge from a high partner-weighted alliance centrality, the firm increasingly reaches saturation of its potential absorptive capacity, and the closer it is to this bottleneck the more difficult it is to incorporate any additional knowledge. This is particularly true when a high diversity of knowledge inputs leads to a random drift in the focal firm's knowledge base, toward different and unrelated domains (Cohen and Levinthal, 1990). This reduces further the limits of its potential absorptive capacity for assimilating new knowledge from its alliance partners (Gilsing et al., 2008). It implies that a higher partner-weighted alliance centrality increases the difficulties of knowledge assimilation that is critical for the development of breakthrough innovation. Because the likelihood and frequency of the random drift in a firm's knowledge base can increase exponentially with more and more diverse knowledge inputs, we expect the negative latent mechanism is curvilinear with an increasing speed.

Second, a high diversity of knowledge inputs, associated with a high partner-weighted alliance centrality, exponentially increases the complexity of knowledge recombination (Fleming, 2001), because it is more and more difficult to recombine dissimilar knowledge components into a successful breakthrough innovation with more diverse inputs (Carnabuci and Operti, 2013). This means that, when the number of knowledge components available for recombining is large, there is likely to be a dramatic reduction in the success rate of discovering breakthrough innovation. Therefore, realized absorptive capacity also increasingly reaches its limits with the assimilated knowledge stemming from a high partner-weighted alliance centrality. Again, we expect that the exponential increase in the complexity of knowledge recombination with increasing partner-weighted alliance centrality makes the negative latent mechanism a curvilinear one.

Therefore, we suggest that partner-weighted alliance centrality could be beneficial for breakthrough innovation, due to the positive latent mechanism, as it means more and more diverse knowledge inputs. The benefits of partner-weighted alliance centrality are, however, likely to increasingly diminish due to the negative latent mechanism, as a firm begins to increasingly struggle with the knowledge diversity and approaches the limits of its absorptive capacity. Taken together, the positive, linear, and negative curvilinear latent mechanisms result in an inverted U-shaped relationship between partner-weighted alliance centrality

and breakthrough innovation,⁵ leading to the following hypothesis.

H1: Partner-weighted alliance centrality has an inverted U-shaped relationship with breakthrough innovation.

The Moderating Effect of Private-Public Ratio

Firms collaborate with both private and public partners (Ahrweiler, Pyka, and Gilbert, 2011; Belderbos, Carree, and Lokshin, 2004, 2006; Bstieler, Hemmert, and Barczak, 2014; Dahlander and Gann, 2010; Das and Teng, 2002; Sherwood and Covin, 2008; Shu, Wang, Gao, and Liu, 2015; von Krogh, Battistini, Pachidou, and Baschera, 2012). To do so is particularly relevant for those looking for breakthrough innovations, for which diverse knowledge inputs are necessary (Schoenmakers and Duysters, 2010). Little is known, however, about how private-public partner heterogeneity interplays with a firm's position in alliance networks in explaining innovation performance. Most prior alliance research has only considered the aggregate impact of all partners, rather than specific types of partners (e.g., Dittrich and Duysters, 2007; Gilsing et al., 2008; Kaufman, Wood, and Theyel, 2000; Sherwood and Covin, 2008; Song and Di Benedetto, 2008; Van Echtelt, Ynstra, Van Weele, and Duysters, 2008).

Clearly, however, firms that simultaneously collaborate with private and public partners will access different kinds of knowledge to those that only collaborate either with private or public partners. The university-industry (U-I) collaboration literature has long recognized the dichotomy between applied and basic knowledge that firms and universities host (Balconi and Laborani, 2006). Firms tend to be market-focused innovators, and make use of applied knowledge that is close to market needs. By contrast, universities tend to be science-focused innovators, which innovate for the sake of adding basic knowledge, and often produce knowledge that is distant to market needs (Gesing et al., 2015; Knudsen, 2007). This means that while firms are likely to choose topics and problems that are valuable for the development of new products and services for customers, universities are likely to choose research topics that are perceived as interesting and valuable by peers (Nelson, 2004). In addition, recent

⁵According to Haans, Pieters, and He (2016), above reasoning indicates additive combination of positive linear and negative curvilinear latent mechanisms resulting in an inverted U-shaped relationship (see Table 1, p. 1179).

research has suggested that firms and universities (or government-funded institutions in general) are dissimilar in both their orientation and in their routines (Estrada, Faems, Cruz, and Santana, 2016), and that, relative to firms, universities' knowledge is often more tacit, and therefore more difficult for firms to learn and to make use of (Kodama, Yusuf, and Nabeshima, 2008). Overall, these differences indicate that the problems that private and public partners may explore in research are very different and the kinds of knowledge outputs each type of partners is interested in diverge (Bruneel, D'este, and Salter, 2010). Firms ally with private partners, therefore, mostly to access new but similar knowledge, and ally with public partners to mainly obtain new and dissimilar knowledge.⁶ Therefore, the composition of a firm's alliances in terms of private-public ratio is likely to affect its access to different kinds of knowledge and associated innovation performance (Faems et al., 2005, 2010).

To theorize the way in which private-public ratio may interplay with partner-weighted alliance centrality to influence breakthrough innovation, we follow recent guidelines in Haans et al. (2016) to systematically explain how private-public ratio affects the positive and negative latent mechanisms. In terms of the positive latent mechanism—in which a higher level of partner-weighted alliance centrality brings more and more diverse knowledge and thereby increases the chance of discovering a breakthrough innovation—we suggest that a higher share of private partners relative to public partners is likely to reduce the benefits of partner-weighted alliance centrality. The rationale is that, on average, two firms will have relatively closer knowledge bases to each other than either will have to a public organization. A greater share of public partners in a firm's alliances, therefore, increases its diversity of knowledge inputs from the alliance network to a larger degree, and a greater share of private partners increases its diversity of knowledge inputs to a lesser degree (Gesing et al., 2015; Knudsen, 2007). This argument is aligned with the insights from prior simulation research showing that firms' collaboration with universities, compared to the collaboration with other firms, increases their knowledge diversity (Ahrweiler et al., 2011). In other words, the benefits of partner-weighted alliance centrality are relatively smaller for a

firm with a higher private-public ratio. Because the positive latent mechanism is linear, such a moderating effect on the positive latent mechanism is viable as a downward move of the turning point of the inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation.⁷

In terms of the negative latent mechanism—in which a higher level of partner-weighted alliance centrality causes increasingly approaching the limits of absorptive capacity, thereby reducing the chance of discovering a breakthrough innovation—a higher share of private partners relative to public partners is likely to alleviate the problems for two reasons. First, a higher share of private partners relative to public partners in a firm's alliances facilitates the assimilation of knowledge inputs from the partners. The firm will, we suggest, be more readily able to realize the value of, acquire and assimilate knowledge inputs from the relatively closer knowledge base of a private partner, and will more quickly reach the limits of its potential absorptive capacity when trying to absorb the knowledge from the relatively more distant knowledge base of a public partner (Cohen and Levinthal, 1990; Todorova and Durisin, 2007). Thus, a larger share of private relative to public partners can alleviate the problem of potential absorptive capacity that arises with increasing partner-weighted alliance centrality when developing breakthrough innovation. Second, a higher share of private partners relative to public partners in a firm's alliances facilitates the transformation and exploitation of assimilated knowledge inputs to create recombination. The firm, we suggest, will be more readily able to transform, to exploit, and to combine the knowledge inputs from the relatively closer knowledge base of a private partner, but will face more difficulty when trying to recombine relatively dissimilar knowledge inputs from a public partner (Carnabuci and Operti, 2013; Fleming, 2001; Savino, Messeni Petruzzelli, and Albino, 2017). Thus, a larger share of private partners relative to public partners can also mitigate the problem of realized absorptive capacity with increasing partner-weighted alliance centrality when developing breakthrough innovation.

These two reasons suggest that the share of private relative to public partners may also weaken the negative latent mechanism. Because the negative latent mechanism is curvilinear, such a moderating effect on

⁶Indeed, prior research shows private firms increasingly use strategic alliances with public partners as a way of reducing their investment in basic research (Bstiler et al., 2014). Science-focused research-oriented institutions are, therefore, becoming increasingly critical for the firm looking to innovate (Ahrweiler et al., 2011; Shu et al., 2015).

⁷According to Haans et al. (2016), above reasoning indicates additive turning point shift (see Table 2, p. 1185): when the moderator weakens the positive linear latent mechanism of an inverted U-shaped relationship, the turning point of the inverted U-shaped relationship will move down.

the negative latent mechanism is manifested as a flattening of the inverted U-shaped relationship (Haans et al., 2016).⁸ Overall, a higher private-public ratio will lower the turning point and flatten the inverted U-shaped relationship, leading to the following hypothesis.

H2: Private-public ratio moderates the inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation, such that a higher proportion of private relative to public partners in a firm's alliances lowers the turning point and flattens the shape of the inverted U-shaped relationship.

Methodology

Empirical Setting

We test our hypotheses using data from the U.S. pharmaceutical industry (SIC code: 2833–2836). We use the pharmaceutical industry as our empirical setting for a number of reasons. First, the pharmaceutical industry is knowledge-intensive, and is known to have a high propensity to patent (Hall and Ziedonis, 2001; Lanjouw and Schankerman, 2004), which means that the industry's innovation outputs can be accurately described by the available patent data. Second, pharmaceutical firms are known to extensively make use of external knowledge, through strategic alliances (Caner and Tyler, 2015; Dong and Yang, 2015; Hoang and Rothaermel, 2005; Rothaermel and Deeds, 2004; Xu, 2015). This implies that the industry is likely to exhibit the sorts of alliance-making behavior that is particularly suitable for testing our hypotheses. Third, the pharmaceutical industry has long been used as an empirical testing ground for innovation research (Dong and Yang, 2015, 2016; Faems, Janssens, Bouwen, and Van Looy, 2006; Gilsing and Nooteboom, 2006; Hoang and Rothaermel, 2005; Powell et al., 1996; Rothaermel and Deeds, 2004; Whittington, Owen-Smith, and Powell, 2009). This makes our approach more comparable to prior work and, therefore, less controversial, in terms of industry-specific conclusion. Fourth, and by focusing on the pharmaceutical industry as a single industry, we are able to control for confounding factors from industry heterogeneities. This

allows us to more fully specify our empirical model and to better ground our conclusion. Finally, the pharmaceutical industry is said to be a conservative industry, which means that any results, in terms of hypotheses testing, will also likely be applicable to less conservative industries.⁹

Data and Sample

We construct our sample using three archival sources of data. First, we built an alliance sample. For this, we used the Thomson Reuters' Securities Data Company (SDC) Platinum database. It documents all alliances and acquisitions, involving the U.S. targets, since 1979. We collected data for all 107,964 alliances announced between 1985 and 2005. Refining this to only include alliances where at least one alliance partner operates in the pharmaceutical industry (SIC code: 2833–2836) reduced the sample to 8,260 alliances. As we need to make use of financial data as controls (e.g., R&D expenditure, sales, etc.), we refined the sample further to only include alliances where at least one partner was a listed firm. Doing so, we built a sample of 2,298 pharmaceutical alliances.

Next, we collected firm-level financial data for each of the alliance participants. For this, we used the Standard and Poor's Compustat database, which is a database of financial, statistical, and market information on active and inactive global companies throughout the world. The Compustat database covers 99% of the world's total market capitalization with annual company data history available back to 1950 and quarterly data available back to 1962. In this study, we used its Fundamental Annual series for North American companies by focusing on the U.S. listed firms. Using the Committee on Uniform Security Identification Procedures (CUSIP) number, a unique 6-digit company code, we identified 2,716 unique U.S. listed pharmaceutical firms in the sample. We then extracted the firm-level financial data (see below for more details) necessary for our analysis of these firms.

Finally, we obtained patent data on each of the sampled firms. For this, we used the National Bureau of Economic Research Patent Citations database (Hall, Jaffe, and Trajtenberg, 2001). This database provides detailed information on all utility patents granted between 1976 and 2006 by the U.S. Patent and Trademark Office (USPTO), which includes 3 million patents and almost 24 million patent citations made by

⁸According to Haans et al. (2016), above reasoning indicates additive flattening (see Table 2, p. 1185): when the moderator weakens the negative curvilinear latent mechanism of an inverted U-shaped relationship, the shape of the inverted U-shaped relationship will flatten.

⁹We thank one anonymous reviewer who suggested this point.

these patents. We conducted a patent-level citation analysis to derive our measure for breakthrough innovation, and then matched the aggregated, firm-level measure for breakthrough innovation to other data, using the Global Company Key (GVKEY), which is a unique 6-digit company code. Since we need to identify a breakthrough innovation based on the forward citations that a firm's patents receive within a five-year period, we could only make use of the patent data up to 2001. Doing so, we created a sample of 722 firm-year observations, involving 196 U.S. pharmaceutical firms, active in patenting and alliance making in the period of 1985–2001.

Key Measures

Breakthrough innovation. Following Srivastava and Gnyawali (2011) and Zheng and Yang (2015), we operationalize breakthrough innovation as the patents that receive forward citations above the 97th percentile of all patents within a particular patent class as breakthrough innovations. Using this definition, we counted the number of such patents, granted to each firm, each year, in each four-digit international patent classification class.¹⁰ Since more recently granted patents had less time to gain forward citations, we counted the forward citations received by each patent in an equal time span of five years. Considering the time lag between knowledge inputs to outputs in the U.S. pharmaceutical industry, we estimated the number of breakthrough innovations using a three-year time lag.¹¹ Following common practice, we also used a one-year lagged measure in a robustness check.

Partner-weighted alliance centrality. Partner-weighted alliance centrality is defined as the degree to which a firm collaborates with other central organizations in the alliance network. We operationalize the partner-weighted alliance centrality by using an eigenvector centrality measure (Bonacich, 1972), which weights a firm's centrality by its partners' centrality in the network as follows. Let $A = a_{ij}$ be the adjacency

¹⁰For robustness check purposes, we also identified breakthrough innovations using the 99th, 98th, 95th, and 90th forward citation percentiles. Consistent results were obtained.

¹¹Due to the fact that a three-year time lag is used for breakthrough innovation in our analysis, and the fact that our patent data end in 2006, we can only count forward citations received by patents granted in 1999–2001 in less than five years. Because all firms in each of these years are allowed to receive forward citations in the same period, however, our results are not likely to be biased, given that we control for year fixed effects by using year dummies. That said, however, we conducted an analysis to test this proportion, by excluding the data for 1999–2001; this revealed consistent results.

Figure 2. Alliance Network of the U.S. Pharmaceutical Industry in 2001. [Color figure can be viewed at wileyonlinelibrary.com]

matrix of the alliance network (set to 1 if there is a tie, and 0 otherwise) in a specific year t , x_i denotes the score of the i th node in a row, and x_j denotes the score of the j th node in a column.

$$x_{it} = \frac{1}{\gamma} \sum a_{ijt} x_{jt} \quad (1)$$

In vector notation, the above equation can be rewritten as

$$X = \frac{1}{\gamma} AX \text{ or } AX = \gamma X \quad (2)$$

Partner-weighted alliance centrality was computed as the greatest eigenvector solution of γ with non-negative entries (Cvetkovic, Doob, and Sachs, 1995).

$$\text{Partner Weighted Centrality}_{it} = \max(\gamma) \quad (3)$$

It is worth noting that we took a complete network approach to construct the alliance network and so calculated the centrality measure based on all alliance data before merging the data to other sources. The “*netsis*” command in Stata was used to calculate the centrality measure (Miura, 2012). Figure 2 illustrates the alliance network that emerged in 2001.

Private-public ratio. The private-public ratio is the ratio of private partners relative to public partners in a firm's alliances. We create private-public ratio as the proportion of firms relative to universities or

Table 1. Sample Distribution

Firm size (M\$)	Obs.	%	Breakthrough innovation	Obs.	%
<1	69	0.10	0	533	0.74
1–10	198	0.27	1–5	136	0.19
11–100	188	0.26	6–10	26	0.04
101–1000	79	0.11	11–20	13	0.02
1001–10,000	114	0.16	21–30	6	0.01
10,000+	74	0.10	30+	9	0.01
Total	722	100	Total	722	100

government-funded institutions collaborating with a focal firm in its alliances. Specifically, we calculated the proportion of private partners in the total number of partners; that is, one minus the number of public partners divided by the total number of partners. The higher the resultant ratio, therefore, the greater the share of private partners, relative to public partners, in a firm's alliances. To calculate the ratio, we first identified the types of partners. Private partners were identified using firm CUSIP number. We identified universities and government-funded institutions by searching the organizational names and descriptions listed in the SDC Platinum database.¹² In our sample, the average firm had 2.09 partners, and with a private-public ratio of 0.91, most of these were private partners. Importantly, however, our sample contains 123 alliances involving a partner as university, and 78 alliances, in which at least one partner was a government-funded institution.

Control Variables

We control for a number of factors that may potentially influence breakthrough innovation. First, because the total number of alliance partners reflects the overall external knowledge resources available to a firm, we control for the number of partners that a firm has (Phelps, 2010). Second, since R&D intensity determines a firm's investment in innovation activity (Cohen and Levinthal, 1990; Wang et al., 2016), we control for the firm's R&D intensity, calculated as

¹²We identified universities by searching for keywords, including “university”—to identify institutions like *Stanford University*—“college” to identify institutions like *Kings College London*—“school”—to identify institutions like *Harvard Medical School*—and “institute”—to identify institutions such as the *Shanghai Institute of Technology*. We repeat this search in German, French, Dutch, Spanish, and Portuguese, to identify universities—such as *Katholieke Universiteit Leuven*—which are often listed in their local languages. We also search for well-known universities—such as *MIT* and *UCLA*—by their abbreviations. We recognize that not all universities are “public,” but we group them as such, arguing that a public and a private university are more similar to each other than a private university and a firm. Similarly, we identified all government-funded institutions by searching the database for keywords, including “Federal,” “National,” “State,” or “City.”

R&D expenditure divided by total sales. Third, we control for the firm's financial leverage, measured by long-term debt divided by total assets, because financial leverage reflects a firm's risk tolerance of conducting innovation activity (Greve, 2003; Wang et al., 2016). Fourth, we control for a firm's prior performance, which is calculated as operating income before depreciation over total assets, because performance feedback is likely to trigger search for innovation (Dong, 2016; Greve, 2003). Fifth, we control for firm size, measured by the natural logarithm of total sales, because firm size may impact a firm's ability to assimilate external knowledge (Dong and Yang, 2015, 2016). Finally, we control for the fixed effect of time by including *year dummies* in all analyses.

Table 1 reports the distribution of our sample by firm size and the number of breakthrough innovations. It shows that the majority of the firms in the sample ($n = 386$) are worth \$1–100 million, although firm size ranges from <\$1 million ($n = 69$) to over \$10 billion ($n = 79$). It reports that the majority of firms in our sample (74%) failed to produce a breakthrough innovation, in support of the suggestion that breakthrough innovations are rare events. Interestingly, Table 1 suggests that a number of firms are serial developers of breakthrough innovation; 9 firms in the sample produced more than 30 in the period. Table 2 reports the descriptive statistics and correlations of our variables.

Analysis Strategy

Since our dependent variable has a count scale and takes only non-negative integer values with a skewed distribution, linear regression models can result in inconsistent, biased, and inefficient estimates (Greene, 2003). A Poisson or negative binomial regression model could be used; however, the Poisson model makes a strong assumption regarding equal mean and variance, which is not applicable in our case (mean = 1.61; SD = 5.40). In such a case of overdispersion, a Poisson model is likely to underestimate the standard errors of the regression coefficients, leading to spuriously high levels of significance (Cameron and Trivedi, 1986). Instead, we used a negative binomial model. Given the panel structure of our data, we cluster by firms and use robust standard errors in all analyses to correct for the correlation of observations from the same firm over the years. Following Aiken and West (1991) and Haans et al. (2016), we estimate the following regression model for firm i in year t to test

Table 2. Descriptive Statistics and Correlations

	Mean	SD	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Breakthrough innovation	1.61	5.40							
(2) Partner-weighted alliance centrality	0.01	0.05	0.03						
(3) Private-public ratio	0.91	0.23	−0.02	−0.06					
(4) Number of partners	2.09	0.45	−0.03	0.31	0.04				
(5) R&D intensity	5.97	51.35	−0.03	−0.01	−0.13	−0.02			
(6) Financial leverage	0.11	0.18	0.06	0.03	0.09	−0.02	−0.05		
(7) Prior performance	−0.13	0.63	0.13	0.04	0.02	0.04	−0.05	−0.29	
(8) Firm size	3.98	3.50	0.38	0.06	0.09	0.07	−0.23	0.12	0.46

the curvilinear effect of partner-weighted alliance centrality and the moderating effect of private-public ratio:

$$\begin{aligned}
 \text{Breakthrough Innovation}_{it+3} &= \beta_0 + \beta_1 \text{Partner Weighted Centrality}_{it} \\
 &+ \beta_2 \text{Partner Weighted Centrality}_{it}^2 \\
 &+ \beta_3 \text{Partner Weighted Centrality}_{it} \times \text{Private Public Ratio}_{it} \\
 &+ \beta_4 \text{Partner Weighted Centrality}_{it}^2 \times \text{Private Public Ratio}_{it} \\
 &+ \beta_j \text{Controls}_{it} + \varepsilon_{it}
 \end{aligned} \quad (4)$$

To test H1, we need to examine β_1 and β_2 . H1 suggests an inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation, requiring $\beta_1 > 0$ and $\beta_2 < 0$ (Aiken and West, 1991, p. 63). To test H2, we need to first examine the impact of private-public ratio on the turning point of the inverted U-shaped relationship and then examine the impact of private-public ratio on the flattening of the inverted U-shaped relationship. Testing the shift of the turning point, we need to test the significance of the equation below, indicating how the turning point changes as private-public ratio changes. Testing for flattening or steepening is equivalent to testing β_4 , where $\beta_4 > 0$ for a significant flattening and $\beta_4 < 0$ for a significant steepening (Haans et al., 2016, p. 1187).

$$\frac{\partial \text{Turning Point}}{\partial \text{Private Public Ratio}} = \frac{\beta_1 \beta_4 - \beta_2 \beta_3}{2(\beta_2 + \beta_4 \text{Private Public Ratio})^2} \quad (5)$$

Results

Testing the Direct Effect

Model (1) reported on Table 3 tests H1, by regressing breakthrough innovation on partner-weighted alliance centrality, and its squared term, as well as control variables. The results show that partner-weighted alliance centrality had a statistically significant and positive effect on breakthrough innovation, suggesting

that collaboration with other central organizations in the alliance network leads to more breakthrough innovations. The negative significance of the squared partner-weighted alliance centrality term suggests, however, that the positive impact of partner-weighted alliance centrality on breakthrough innovation is diminishing. Overall, these results suggest an inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation. Thus, H1 is supported.

Figure 3 plots the curvilinear relationship between partner-weighted alliance centrality and the number of breakthrough innovations based on regression results. It shows that the number of breakthrough innovations increases with partner-weighted alliance centrality, but with a decreasing slope, before turning, and declining. The turning point of the curve appears when partner-weighted alliance centrality is equal to 0.18. Partner-weighted alliance centrality varies from 0 to 0.66 in our sample, suggesting that a firm can achieve the highest number of breakthrough innovations when its centrality is about one third (27%) of the maximum. Beyond this threshold, the number of breakthrough innovations declines with increasing partner-weighted alliance centrality.

Testing the Moderating Effect

Model (2), in Table 3, tests H2, by adding private-public ratio, and its interaction term with both partner-weighted alliance centrality and squared partner-weighted alliance centrality, to Model (1). The results suggest that private-public ratio had a statistically significant and negative interaction effect with partner-weighted alliance centrality on breakthrough innovation. Interestingly, the result suggests that private-public ratio also had a statistically significant and positive interaction effect with the squared partner-weighted alliance centrality on breakthrough innovation. To formally test the moderation effect, we followed the guidelines of

Table 3. Negative Binominal Regression Results for Breakthrough Innovation

	(1) Curvilinear model	(2) Full model	(3) Heckman model	(4) One-year time lag	(5) 99th percentile	(6) 90th percentile
Partner-weighted alliance centrality	17.59*** (4.77)	34.03*** (6.58)	33.61*** (6.51)	29.80** (13.75)	30.45*** (7.76)	28.08*** (5.43)
Partner-weighted alliance centrality ²	−50.15*** (13.24)	−90.44*** (15.68)	−89.02*** (15.94)	−80.36*** (33.12)	−84.08*** (17.30)	−77.27*** (14.26)
Partner-weighted alliance centrality × Private-public ratio		−24.44** (11.84)	−24.39** (11.43)	−25.73 (15.90)	−24.85** (11.15)	−20.73*** (7.70)
Partner-weighted alliance centrality ² × Private-public ratio		60.21** (30.04)	59.37** (29.39)	76.51*** (36.42)	64.98** (26.00)	62.02*** (17.94)
Private-public ratio		0.38 (0.56)	0.41 (0.55)	−0.43 (0.52)	0.00 (0.56)	0.25 (0.41)
IMR			−9.72 (11.48)			
Number of partners	−0.35 (0.23)	−0.35 (0.23)	−0.52 (0.29)	0.00 (0.11)	−0.29 (0.21)	−0.04 (0.29)
R&D intensity	0.00 (0.00)	0.00 (0.00)	−0.00 (0.00)	0.02** (0.01)	0.00** (0.00)	0.00 (0.00)
Financial leverage	−0.79 (0.90)	−0.76 (0.90)	−1.22 (1.11)	−0.47 (0.38)	−0.20 (1.03)	−1.46* (0.84)
Prior performance	−0.20 (0.19)	−0.21 (0.19)	−0.28 (0.19)	−0.79 (0.53)	−0.25 (0.19)	−0.19 (0.27)
Firm size	0.42*** (0.06)	0.42*** (0.06)	0.21 (0.28)	0.54*** (0.05)	0.45*** (0.08)	0.44*** (0.04)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	−5.55*** (0.65)	−5.54*** (0.90)	10.68 (19.28)	−4.78*** (0.70)	−6.06*** (0.93)	−6.09*** (0.96)
Wald Chi-square	520.32***	536.80***	519.54***	499.45***	460.36***	741.84***
<i>n</i>	722	722	722	1236	722	722

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Clustered robust standard errors are in parentheses. Dependent variable is the number of breakthrough innovations.

Figure 3. Partner-Weighted Alliance Centrality and Breakthrough Innovation. [Color figure can be viewed at wileyonlinelibrary.com]

Haans et al. (2016, p. 1187), and conducted the following tests.

First, and to test the shift of the turning point, we estimated equation (5) above.¹³ Doing so, we found that the effect of private-public ratio on the turning point at the mean of private-public ratio (0.91) was statistically nonsignificant ($\beta = -102420.40$, $p = 0.40$). This suggests that private-public ratio does not affect the positive latent mechanism, indicated by a nonsignificant shift of the turning point of the inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation. In other words, collaborating with more private partners, relative to public partners, does not affect the positive latent mechanism through which partner-weighted alliance centrality influences breakthrough innovation.

Next, and to determine if the shape is flattening or steepening, we considered the regression coefficient. The coefficient of the interaction term between the squared partner-weighted alliance centrality and private-public ratio solely determines whether the inverted U-shaped relationship is flattening or steepening; the relationship is flattening if the coefficient is positive and steepening if the coefficient is negative (Haans et al., 2016, p. 1187). Since, in our case, this coefficient was statistically significant and positive ($\beta = 60.21$, $p < 0.05$), we conclude that the inverted U-shaped relationship flattens with increasing private-public ratio. This suggests that private-public ratio does affect the negative latent mechanism, leading to a significant flattening of the inverted U-shaped relationship between partner-

weighted alliance centrality and breakthrough innovation. In other words, collaborating with more private partners, relative to public partners, weakens the negative latent mechanism through which partner-weighted alliance centrality influences breakthrough innovation. Thus, H2 is partially supported.

To visually illustrate the moderating effect of private-public ratio, we plotted the inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation at different proportions of private relative to public partners in Figure 4. We use one standard deviation below the mean ($0.91 - 0.23 = 0.68$) as the low level of private-public ratio and the mean (0.91) as the high level of private-public ratio due to the fact that one standard deviation above the mean is greater than 1 and therefore unfeasible. While Figure 4 shows that the turning point of the curve at a high level of private-public ratio is below the turning point of the curve at a low level of private-public ratio, a formal test suggests that the difference is statistically nonsignificant (Chi-square = 1.35, $p = 0.24$). However, the curve at a high level of private-public ratio is significantly flattening compared to the curve at a low level of private-public ratio ($\beta = 60.21$, $p < 0.05$), which is consistent with the regression results.

Overall, therefore, our results suggest that private-public ratio only moderates the negative latent mechanism rather than the positive latent mechanism. Interestingly, therefore, a greater private-public ratio slows down the diminishing speed of the inverted U-shaped relationship (e.g., flattening shape) but it does not significantly reduce the optimal number of breakthrough innovations (e.g., lower turning point).

Robustness Checks

Our results are not likely to be driven by reverse causality, because we used a relatively long (i.e., three-year) time lag between the independent and the dependent variables. However, we recognize that partner-weighted alliance centrality may be endogenously determined, making our estimates not consistent. This is because a firm's partner-weighted alliance centrality is likely to be self-selected due to the fact that a technological leader faces more opportunities to partner with other central organizations in an alliance network (Ahuja, 2000). If so, firms with a high impact on technological development are likely to form more alliances with other central organizations, making

¹³This can be estimated in Stata with the “nlcom” command.

Figure 4. Partner-Weighted Alliance Centrality and Breakthrough Innovation at Varying Proportions of Industry Relative to Public Partners. [Color figure can be viewed at wileyonlinelibrary.com]

partner-weighted alliance centrality endogenously determined. We therefore checked for potential endogeneity, using a two-stage Heckman model.¹⁴ To do so, we followed the procedures suggested by Shaver (1998), and created a dummy variable indicating the level of a firm's partner-weighted alliance centrality as high (i.e., above the median) or low (i.e., below or equal to the median). In the first stage, we used a Probit model to regress this dummy variable on a firm's total number of forward citations received (as a proxy of its impact on technological development) and all control variables. The Probit model demonstrated a good fit (Wald Chi-square = 188.74, $p < 0.001$), allowing us to calculate the Inverse Mills ratio (IMR), to represent the propensity of high centrality that is endogenously determined. In the second stage, we then retested our hypotheses with IMR as an additional control for this endogenous propensity. Model (3) in Table 3 presents our results. It not only supports our hypotheses, but because IMR is not statistically significant, it indicates an absence of endogeneity too.

We conducted a number of sensitivity analyses to confirm the robustness of our results. First, and following common practice, we re-estimated our result using a one-year time lag, instead of the three-year lag used in our main analysis. Model (4), in Table 3, reports the results. It shows that, using this alternative measure for breakthrough innovation, both hypotheses are also supported. Second, we used different percentiles (99th, 98th, 95th, and 90th) of forward citations to measure breakthrough innovation, instead of the 97th percentile used in the main analysis. Similar to prior findings (e.g., Zheng and Yang, 2015), we found

qualitatively similar results supporting H1 and H2. For example, Model (5) and (6) report the results using 99th and 90th percentiles of forward citations to measure breakthrough innovation.¹⁵ Overall, therefore, we conclude that our results are robust.

Discussion

Theoretical Implications

Prior research suggests that the internal organization of firms, which is designed to assure efficiency in daily operations, is even at odds with the pursuit of breakthrough innovation (O'Connor and De Martino, 2006). Consequently, firms often look to acquisitions or to alliances when developing breakthrough innovation, which however carry their own risk (von Krogh et al., 2012). In particular, strategic alliances involve numerous challenges for selecting partners when their aim is to develop breakthrough innovation. In this article, we fill two gaps in our understanding about how to organize alliance networks for increasing the likelihood of achieving breakthrough innovation: (1) to what extent the position of the firm in interorganizational collaboration networks—in terms of partner-weighted centrality—leads to the development of breakthrough innovation, and (2) under what conditions—in terms of partner heterogeneity in private-public collaboration—this impact may vary.

We have two key findings. First, we find support for our hypothesis that firms working with other central organizations in an alliance network are more likely to be exposed to the sorts of knowledge necessary to develop breakthrough innovation, but that, beyond a certain point, these firms have a reduced rate of success, in terms of developing breakthrough innovation, as they reach the limits of their absorptive capacity. Second, we find support for our hypothesis that the types of partners moderate the inverted U-shaped relationship between partner-weighted alliance centrality and breakthrough innovation, as more private partners, relative to public partners, stem the declining benefits of partner-weighted alliance centrality for developing breakthrough innovation. Interestingly, however, and using recently advanced techniques for teasing out the moderation of curvilinear relationship (Haans et al., 2016), we find that the ratio does not significantly affect the turning point of the inverted U-shaped relationship, but that it flattens

¹⁴We thank one anonymous reviewer who suggested this test.

¹⁵The results based on other percentiles are available upon request.

the shape. This indicates that though more private partners relative to public partners do not substantially reduce the diversity of knowledge inputs to a focal firm, the focal firm can more easily digest the external knowledge from its private partners and can tolerate more private partners than public partners when developing breakthrough innovation.

In doing so, we investigate important principles applied in the organization of interorganizational collaboration networks for breakthrough innovation. First, and in light of the fact that firms tend to collaborate with other organizations that are central in an alliance network to get access to more and more diverse external knowledge that is necessary for breakthrough innovation (Schoenmakers and Duysters, 2010), we show that it is important for a firm, searching for breakthrough innovation, to choose its position by considering its partners' positions in an interorganizational collaboration network. We show that by choosing partners that are not very central or centrifugal, the firm can reduce the problems of absorbing external knowledge while promoting breakthrough innovation. To the best of our knowledge, we are the first to theorize and to test the impact of alliance network centrality in the context of breakthrough innovation, and we do so using a more fine-grained centrality measure, which not only takes into account how many alliance partners a firm has, but also how central its partners are.

Second, and in light of the fact that a firm may broaden its collaboration by incorporating public partners given the fact that private and public partners own different kinds of knowledge (Gulbrandsen et al., 2011) and present different opportunities and challenges for developing breakthrough innovation, we show that it is important for a firm, searching for breakthrough innovation, to carefully select the types of partners in its alliances. We show that collaboration with private partners, relative to public partners, alleviates the problems associated with absorbing external knowledge and enables the discovery of breakthrough innovation. To the best of our knowledge, we are the first to consider how the private-public partner heterogeneity in a firm's alliances impacts the likelihood of developing breakthrough innovation. In doing so, we contribute to the breakthrough innovation literature, and to the theme of this special issue. We identify organizational arrangements, which are conducive to breakthrough innovation, and provide managers with real-world tools for increasing the likelihood of achieving breakthrough innovation.

Managerial Implications

While breakthrough innovation is sometimes thought to be the result of good fortune, our results show that managers can actively manage the likelihood that their firms develop breakthrough innovation by carefully selecting collaborative partners in strategic alliances. We find that firms with central partners are more likely to develop breakthrough innovation. However, after a certain point, the benefits of collaborating with other central organizations in the alliance network for developing breakthrough innovation drops. Thus, it is not a simple case of "the more central partners the merrier" when it comes to building interorganizational collaboration networks. While prior research suggests that a technological leader faces more opportunities to form alliances with other organizations (Ahuja, 2000), our results suggest that the firm may run into problems with its absorptive capacity when developing breakthrough innovation in collaboration with other central organizations.

There are a number of ways in which managers could look to overcome these limitations. First, the manager could look to expand their firms' absorptive capacity by hiring additional knowledge experts, or by building multidisciplinary teams that help to deal with diverse knowledge inputs. Admittedly, this would only work for a fixed increase in knowledge diversity, and additional diversity would require an additional investment in absorptive capacity. Second, the manager could become more "choosy." Managers, we suggest, could foster breakthrough innovation by collaborating with organizations that are not very central or peripheral in the alliance network, making their knowledge inputs more digestible. Third, and as our finding suggest, managers could combine both strategies, and choose to work with more "easy-to-collaborate-with" private partners. Our results suggest that private-public partner heterogeneity moderates the relationship between partner-weighted alliance centrality and breakthrough innovation. This suggests that the problems with absorptive capacity can, in principle, be partly overcome by choosing to work with more private partners. Our findings suggest that firms with a greater share of private partners, relative to public partners, are more likely to develop breakthrough innovation.

Limitations and Future Research

As with all research, ours has its limitations. Beyond the usual limitations of results based on a single

industry—however conservative, and patents as a certain form of innovation—however commonly used, our study has several noteworthy limitations.

First, we define a patent as a breakthrough innovation if it is in the 97th percentile of forward citations that are received in a patent class within five years. We not only use this measure because it has been used in recent literature, but also because breakthrough patents are, conceptually, rare occurrences. The robustness checks that we conducted suggest that our results hold, using broader alternative measures for breakthrough innovation, but the question still remains here—and indeed in the wider literature—as to what precisely constitutes a breakthrough innovation. Future research may develop and use other measures for breakthrough innovation to examine our findings.

Second, we distinguish between private and public partners. We do not, however, in terms of their operating description, and do not distinguish partners in greater detail, for example, private partners in terms of suppliers, customers, and competitors, or public partners in terms of top-tier universities and the rest, etc. We do so because we are unable to distinguish between the types of private partners at a more detailed level. We hope that future researchers, therefore, will collect data for subcategorizing alliance partners even at the project level.

Third, we suggest, and find, that beyond an optimal point, firms that partner with central organizations run into problems related to potential and realized absorptive capacity. In both cases, the consequences for breakthrough innovation are the same; however, the actual reason underlying this remains unclear given the level of our analysis. We hope that future study will concretely pin down the problem by collecting more detailed data.

Last but not least, we acknowledge that we are using only a relatively small subset of all the alliances that took place in the research period. That said our sample includes 30% of the alliances in the pharmaceutical industry, and 100% of the pharmaceutical alliances in the period that include at least one public partner. We are confident, therefore, that our sample is representative, and large enough to carry out our analysis, and to draw conclusions.

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