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Which signal to rely on? The impact of the quality of board interlocks and inventive capabilities on research and development alliance formation under uncertainty

Bilian Ni Sullivan
Hong Kong University of Science and Technology, Hong Kong

Yi Tang
Hong Kong Polytechnic University, Hong Kong

Abstract

In this study, we demonstrate that the quality of a firm's *board interlocks* and a firm's *inventive capabilities* can serve as signals of its quality as a research and development alliance partner to other firms. The extent of the signaling effects, however, varies under different types of uncertainty. Using research and development alliance, patent and board interlock data from the US biotechnology industry during the period 1990–2003, we find that the board interlock quality as well as the strength and focus of a firm's inventive capabilities have positive and significant effects on the likelihood of research and development alliance formation. Importantly, we further find that the impact of the strength of a firm's inventive capabilities is weaker, while the impact of the quality of the firm's board interlocks is stronger, under both market uncertainty and firm-specific uncertainty. The implications for studies of board interlocks, uncertainty, and research and development alliances are discussed.

Keywords

Board interlock, inventive capability, R&D alliance, uncertainty

It has been well documented in the literature of network studies that board interlocks, which are formed when the executives or directors of one firm sit on the board of directors of another firm, can affect many important firm activities (e.g. Beckman and Haunschild, 2002; Davis, 1991; Shipilov et al., 2009; Westphal, 1998). Extensive empirical studies of board interlocks reveal that board interlock networks can serve as conduits or pipes for information exchange among the firms,

Corresponding author:
Bilian Ni Sullivan, Department of Management, School of Business and Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.
Email: mnbilian@ust.hk

leading to the diffusion of various managerial practices (Haunschild, 1993; Mizruchi, 1992; Palmer et al., 1993; Westphal and Zajac, 1997). The existing literature on board interlocks, however, has not paid sufficient attention to the role of board interlocks as "prisms" that provide informative cues about the focal firm and subsequently affect the decision-making processes of other firms (Podolny, 2001). As a result, our understanding of the effects of board interlocks on firms' decision-making processes remains incomplete.

In this study, we investigate whether and how board interlocks act as "prisms" signaling certain information to the market audience and affect the formation of a firm's research and development (R&D) alliances with other firms. As the informational cues about the focal firm to others can come from multiple facets related to the firm (Ozmel et al., 2013) and firms' internal conditions also affect the formation of strategic alliances (Stuart, 1998), we further compare the impact of board interlocks with the signaling effect of a firm's inventions on firms' R&D alliance formation under uncertainty. We argue that the quality of the board interlocks and the firm's inventive capabilities can provide informational cues about the focal firm and thus affect the attractiveness of the focal firm as an alliance partner. We further argue that under heightened uncertainty, other firms tend to pay more attention to board interlocks for informational cues and that consequently, the impact of board interlocks is strengthened while the effects of firm inventive capabilities as informational cues is weakened.

Our study makes important and timely contributions to the literature for the following reasons. First, differing from other types of firm networks, such as firm alliances (Ahuja, 2000; Stuart, 1998), syndicates (Podolny, 2001) or buyer–supplier ties (Hoetker et al., 2007), board interlocks can directly affect the monitoring and advisory role of the board which plays a central role in corporate governance (Hallock, 1997). Recent studies on the impact of board interlocks on corporate governance suggest that a well-connected board of directors might be conducive to a board's advising ability but could be detrimental to its monitoring function (Hwang and Kim, 2009; Larcker et al., 2005). While previous research in this stream tends to focus on the information-exchange function of board interlocks (Beckman and Haunschild, 2002; Haunschild and Beckman, 1998), our study provides a new angle to understand the role of board interlocks by highlighting that a firm's state of governance can be assessed by other firms through observing the firm's interlocks, which in turn affects the subsequent strategic decisions (e.g. R&D alliance formation) made by those firms. In particular, we focus on the signaling role of the quality of the board interlock ties as indicated by certain characteristics of the interlocked firms since other firms are sensitive to the characteristics of both the board members and their associated firms. For instance, research has found that the stock market responds differently depending on who is sitting on the board (Brickley et al., 1995). We further demonstrate that when signals related to a firm's technological capabilities are weaker, board interlocks as the signal source to other firms can become a more robust alternative.

Second, we advance the understanding about the signaling role of firm invention in the formation of R&D alliances by analyzing the impact of two dimensions of firm inventive capabilities: strength and focus. A firm's inventive capability refers to its ability to pursue inventions by recombining existing ideas and knowledge. We focus on the inventive capabilities of a firm because firm invention is closely related to a firm's R&D activities and is essential to a firm's competitiveness (Khilji et al., 2006). According to Schumpeter (1934), invention, innovation (commercialization or adoption of invention), and diffusion are three necessary steps for a creative economy. Invention can be understood as a process of recombining existing ideas, concepts, or physical materials (Nelson and Winter, 1982; Fleming, 2001). Nevertheless, the existing research has rarely paid attention to the two distinct dimensions of firm inventive capabilities: a firm possesses strong inventive capability (i.e. the strength aspect) if it can generate many inventions; it has a focused

inventive capability (i.e. the focus aspect) if its inventions fall within a few technological categories only. We contend that both dimensions could play an important signaling role in R&D alliance formation. More importantly, our study makes additional novel contributions by showing how a firm's inventive capability exerts a different impact on the formation of R&D alliances from the board interlocks under the influence of uncertainty.

Third, our study can further our understanding of the determinants of R&D alliance formation. Our choice of R&D alliances as a research context is based on the fact that firm R&D alliances can determine a firm's competitiveness in an industry (Powell et al., 1999). Strategic alliances are cooperative agreements between firms designed to achieve certain strategic goals (Das and Teng, 2000; Rowley et al., 2000; Teng, 2007), and R&D alliances are formed specifically to enable collaboration in the area of R&D (Sampson, 2007). Firms, especially those in knowledge-intensive industries, such as the biotech industry, have extensively used R&D alliances as a tool to learn new skills and knowledge, to pursue new product development, to gain access to complementary knowledge, and to spread risks associated with the new product development (Hoang and Rothaermel, 2005; Mowery, 1988; Powell et al., 1996). Studies on the determinants of R&D alliance formation have examined the impact of firm size, market share, firm past experience as well as the influence of market concentration, and domestic and foreign competition (e.g. Li et al., 2008; Link and Bauer, 1989; Roller et al., 2007; Sakakibara, 2002; Urban and Vendemini, 1992). However, research has rarely examined if and how board interlocks exert influences on the formation of R&D alliances. In addition, the literature contains limited discussions on the comparison of the effect of interfirm network ties and the effect of firm capabilities in the context of R&D alliance formation. Therefore, our studies serve as a useful attempt to shed light on the formation of R&D alliances by highlighting the signaling role of board interlocks and by providing a systematic examination of the impact of a firm's relational ties and internal capabilities on R&D alliance formation.

To compare the signaling impact of board interlocks with that of firm inventions, we examine the contingent role of uncertainty. Uncertainty in our study is understood as "… the difficulty firms have in predicting the future, which comes from incomplete knowledge" (Beckman et al., 2004: 260). Following Beckman et al. (2004), we consider two distinct types of uncertainty: market uncertainty and firm-specific uncertainty. Whereas market uncertainty is linked to a firm's external market environment and faced by all firms in that environment, firm-specific uncertainty stems from a variety of sources unique and often internal to a firm (Beckman et al., 2004). The two concepts are similar to the systematic and nonsystematic risk in the finance literature (Beckman et al., 2004), both suggesting that firms in the market do not have a clear view of the future. In their study on the influence of uncertainty on new network tie formation, Beckman et al. (2004) found that in general, neither market uncertainty nor firm-specific uncertainty directly affects the broadening of alliance ties (or interlock ties). Extending their study, we suggest that these two types of uncertainty can differentiate between the signaling effects of board interlocks and firm inventions. As firms will in general try to reduce the level of uncertainty (Hogg and Terry, 2000), under a heightened level of uncertainty, other firms may modify their ways of assessing the quality of the focal firm so to reduce the level of uncertainty.

Theory and hypotheses

R&D alliances: the impact of board interlocks

In the knowledge-intensive industries, such as the biotech industry, there is an increasing need for firms to form R&D collaborations with others to acquire knowledge and new skills, develop new capabilities, foster innovation, and reduce the risks associated with development (Powell et al.,

1996; Sampson, 2007). Different from other types of strategic alliances, R&D alliances typically involve high levels of knowledge transfer, uncertainty, and time commitment, making it extremely important for firms to select proper partners (Li et al., 2008). The success of the knowledge transfer is based not only on firms' knowledge base or capabilities but also on their being able to offer proper incentives to motivate alliance partners to exchange certain knowledge (Sampson, 2007). Furthermore, firms also need to consider the risk of value erosion of their own knowledge base in such alliances (Li et al., 2008).

The current literature reveals that the formation of R&D alliances may not follow the same pattern as the formation of other types of alliances. For instance, Li et al. (2008) found that given the peculiar nature of R&D, the benefits of being prior network partners (Gulati, 1995) are dependent on the kind of prior/new partnership formed with the focal firm. In the context of R&D alliances, it was suggested that prior relationships carry benefits, such as smooth knowledge transfer, but also risks, such as knowledge appropriation (Li et al., 2008). We contend that given such a nature of R&D alliances and the necessity for firms in knowledge-intensive industries to form alliances with others, firms must be able to quickly make sound judgments about the quality of particular firms of interest. Therefore, the role of informational cues about the focal firm's quality can be more predominant in the selection of R&D alliance partners.

The industry and firm context of our study further suggest the existence of the signaling mechanism in the process of R&D alliance formation. We focus on young US firms (founded after 1990 and aged 13 years or under in our sample period) in the emergent biotech industry, which has experienced rapid growth in recent years (Weintraub, 2004). For young firms, it is often difficult to find alliance partners due to their own lack of track records (Hsu, 2006). Research reveals that young firms do engage in certain activities, such as affiliating with reputable firms, to signal their quality (Pollock et al., 2010). The difficulties faced by young firms in forming R&D alliances with others can be more pronounced in the biotech industry since the risk and uncertainty surrounding R&D activities in this industry are much higher (DiMasi, 1995; Xu, 2005). The situation is exacerbated by the fact that young firms have not fully established themselves in the industry. Thus, it is truly a formidable task for young firms to find willing R&D alliance partners. Consequently, signals from the focal firm that can be used by other firms to infer its quality are essential for its R&D alliance formation.

One of the important signals that are informative about the quality of the firm, especially the state of firm governance, is the quality of board interlocks. Relative to other relational ties, board interlocks have certain advantages in signaling the quality of the firm. First, all publicly traded firms in the United States are mandated to have a board of directors with a minimum of three persons (Mizruchi, 1996). A board typically has inside and outside directors. The inside directors are the members of the focal firm, and the outside directors are those with primary affiliations to other firms. Board interlocks are generated when the inside directors also sit on other firms' boards or the focal firm brings outside directors to serve on its board (Mizruchi, 1996). For public firms, the information on the board composition and the connections among the firms through their boards of directors is readily available to the public. On the contrary, certain information on other types of network ties, such as the detailed terms and termination dates of alliances, could be relatively more difficult to acquire through public information channels.

While the signaling role of board interlocks in alliance formation has been largely left unexplored, in the broad literature of network studies, we do have empirical evidence to support the argument that a firm's structural or positional advantages can be conducive to alliance formation (Stuart, 1998). Using the alliance network as a context, for instance, Gulati (1995) revealed that the

more previous alliances the partners have, the less likely they are to be engaged in equity alliances due to the trust developed between the partners. Vanhaverbeke et al. (2002) further revealed that direct ties between alliance partners, alliance network distance, and alliance network centrality can affect the preference of firms for subsequent alliances. Based on patent data, Stuart (1998) found that technology connections among firms determine their technical crowding and prestige in a particular technology field, influencing the availability of partners and firm status as perceived by potential alliance partners.

Different from the interfirm network ties in those studies, board interlocks can directly affect the functions of the board which plays a central role in corporate governance. Prominent or high-quality board interlocks of the focal firm serve to signal its governance quality to potential alliance partners, increasing its attractiveness to them. First, high-quality network partners in board interlocks serve to reduce uncertainty about the managerial quality of the focal firm. In the process of forming R&D alliances, other firms in the market will evaluate the focal firm's unobservable quality by noting the focal firm's connections. If high-quality or reputable members sit on the firm's board, other firms are likely to have a favorable view of its top management (Mizruchi, 1996). The uncertainty surrounding the managerial quality of the focal firm can thus be reduced. Furthermore, as a conduit for information diffusion, board interlocks can affect multiple aspects of firm decision-making processes and choices, such as acquisition premiums (Beckman and Haunschild, 2002) and the adoption of certain corporate practices (Davis, 1991; Haunschild, 1993). Therefore, firms with well-respected interlocking partners would be regarded as having a better chance of making sound managerial choices.

Second, association with highly reputable network players in general ensures the managers of a firm have access to more resources and other benefits. For instance, research has revealed that investors favor those young firms that have prominent strategic alliance partners (Stuart et al., 1999). Firms can also acquire legitimacy through social connections with other prominent firms (Galaskiewicz, 1985). Consequently, the confidence of other firms in the focal firm's ability to acquire resources from the external environment can be enhanced. Perceived sound governance can also enhance other firms' confidence in the focal firm's ability to adequately utilize such resources and benefits.

Thus, we offer the following hypothesis:

Hypothesis 1. A firm having higher quality board interlocks is more likely to form an R&D alliance.

Signaling effects of board interlock quality and inventive capabilities under uncertainty

Various studies of signaling effects on firms' choices, decision-making processes and outcomes indicate that multiple/many factors can serve to indicate a firm's quality (Ozmel et al., 2013; Pollock et al., 2010). However, the question that remains to be answered is, do the signaling effects of different factors change in magnitude or direction under certain circumstances, and if so, how?

Since firm internal characteristics have been suggested as important alternatives to a structural perspective in explaining alliance formation (Das and Teng, 2000; Eisenhardt and Schoonhoven, 1996; Glaister and Buckley, 1996; Mitsuhashi and Greve, 2009; Pisano and Teece, 1989), in the following, we pay particular attention to the signaling effects of firm inventions. We propose that while a firm's inventive capabilities and the quality of its board interlocks can both signal its attractiveness

as an R&D alliance partner, the effects will change under a higher level of uncertainty. In the following, we first establish the relationship between firm inventive capabilities and R&D alliance formation, and then develop hypotheses about the moderating impact of uncertainty.

Signaling effects of inventive capabilities. While prior research has suggested that firm technological competency can influence the formation of strategic alliances (Ahuja, 2000), few have specifically examined the impact of inventive capabilities on the formation of R&D alliances. Extending this line of research, we present a more comprehensive picture of a firm's inventive capabilities as a source of attraction to other firms for R&D alliance formation by addressing two dimensions of inventive capability: capability strength and capability focus. We contend that both the strength and the focus of a firm's inventive capabilities can act as signals to other firms. While firms with strong inventive capabilities receive positive reactions from other firms, firms with less focused inventive capabilities (i.e. firms that span multiple technological categories) can generate negative reactions.

Firms can develop their inventive capabilities through accumulated learning and continuous investments in invention activities. The variations in terms of learning, resource allocation and efforts devoted to inventive activities can be reflected in the strength of inventive capabilities. Firms with strong inventive capabilities can produce more inventions. Since R&D collaborations involve extensive exchanges of knowledge, the focal firm's ability to generate new ideas and knowledge can be an essential factor affecting its attractiveness to other firms.

A firm's inventive capabilities can be a significant part of its "technology capability," which can be understood as the knowledge and skills necessary for firms to select, use, and further develop technologies (Cohen and Levinthal, 1990). In a context where research is very costly and later developments require participation in early research, firms that have failed to develop strong technology capabilities will seek to acquire such capabilities through R&D partnerships with firms that have succeeded in doing so (Ahuja, 2000). As firms will want to learn from others with strong capabilities (Baum et al., 2000), those firms with strong inventive capabilities are certain to be more attractive.

Furthermore, firms with strong inventive capabilities can be attractive to those with skills and resources to commercialize invented products. Invention and commercialization often require firms to have distinctively different skills and resources (Roberts, 1988; Teece, 1986). Joint alliances play an important role in commercializing inventions (Jung, 2009). Firms that are strong on the commercialization of invented products (e.g. raising capital, marketing, manufacturing, or distributing) may look for partners with strong inventive capabilities early on in hopes of commercially benefitting from future developed products.

Finally, a firm's inventive capabilities to a large extent indicate its ability to create links to its existing knowledge, since innovation normally involves the recombination of existing technology components (Fleming, 2001). This process of recombining existing knowledge is a process of incorporating accumulated past knowledge into current organizational routines. This ability to continuously learn, recombine existing knowledge, and generate new knowledge is essential for developing technological capabilities (Dosi, 1988). Thus, firms possessing this ability will make attractive targets for other firms who desire to acquire or strengthen this ability through R&D alliances.

The above arguments lead us to the following hypothesis:

Hypothesis 2. A firm having stronger inventive capability is more likely to form an R&D alliance.

The role of capability focus in alliance formation has largely been left unexplored in extant literature. We argue that the lack of focus of a firm's inventive capability will send confusing signals to other firms, leading to negative reactions from them. The focus of a firm's inventive capabilities can be manifested by its spanning multiple industry or technological categories. The more categories a firm is involved in, the less focused are its inventive capabilities. A firm with more focused inventive capabilities can engage in both exploitative and exploratory activities. For instance, in the process of recombining existing technological components, firms may repeatedly use certain components, reflecting the nature of exploitation (March, 1991), but these repeatedly used components may be used with other new components, reflecting the nature of exploration (March, 1991). Therefore, the focus of inventive capabilities can be independent of the scale or the true quality of the inventions.

We argue, however, that the focus of inventive capabilities can affect how other firms perceive the focal firm. A reduced level of focus could cause other firms to become confused about the focal firm's identity and induce negative reactions from them. Recent studies on firms' social identities propose that a firm's identity can be understood as a set of social codes that "specify the properties that an entity can legitimately possess" (Pólos et al., 2002: 85). Studies have revealed that firms spanning different categories tend to signal illegitimacy to other firms, consequently leading to doubts about the firms' quality and signaling poor performance (Hsu, 2006; Hsu et al., 2009; Zuckerman, 1999). For instance, Zuckerman (1999) found that as a firm moves into multiple categories of activities, it tends to be perceived as less competent in each category and is more likely to have a difficult time projecting a visible image to others. With unclear signals about a firm's core capabilities, negative evaluations tend to follow. Since firms look for legitimate signals in the process of forming relationships with other firms and prefer to be with legitimate players in the field (Galaskiewicz, 1985; Sullivan et al., 2007), the reduced perceived legitimacy about the focal firm's inventive capabilities because of its spanning multiple categories will reduce its opportunities to form R&D alliances with other firms. The above arguments suggest that having focused inventive capabilities can increase the attractiveness of a firm in the partner selection process.

Hypothesis 3. A firm having more focused inventive capability is more likely to form an R&D alliance.

The moderating effect of uncertainty. If both the quality of board interlocks and inventive capabilities can signal a firm's quality as an R&D alliance partner, do the two signaling effects vary under different levels of uncertainty? As mentioned earlier, uncertainty is related to actors' inabilities to predict future outcomes accurately due to insufficient information (Beckman et al., 2004; Carpenter and Fredrickson, 2001; Milliken, 1987; Thompson, 1967). It has been argued that a firm's actions are strongly influenced by uncertainty (Beckman et al., 2004; Hogg and Mullin, 1999). For instance, when outsiders are more uncertain about a supplier's quality, status of the buyers becomes more important (Hoetker et al., 2007). Firms tend to rely on different organizational designs and certain governance structures to cope with both market and firm-specific uncertainty (Pfeffer and Salancik, 1978; Thompson, 1967; Williamson, 1981). Alliance formation can be directly affected by uncertainty. For instance, it was argued that firms are more likely to form alliances under a higher level of uncertainty (Pfeffer and Salancik, 1978). Beckman et al. (2004) revealed that under high market uncertainty, firms are more likely to reinforce existing alliance ties, and under high firm-specific uncertainty but low market uncertainty, firms are more likely to build new alliance ties.

The effectiveness of the board interlock quality and inventive capabilities as signals in the process of R&D alliance formation can be affected by the reliability of each signal as perceived by other firms and the relative cost of inferring valuable information from the signals. We argue that the signaling effect of inventive capabilities on the formation of R&D alliances becomes weaker with an increased level of uncertainty for the following reasons. First, under high degrees of market and firm-specific uncertainty, other firms are less likely to perceive inventive capabilities as a reliable signal for the quality of a potential partner because the perceived value of a firm's inventive capabilities and the corresponding new technologies can become highly ambiguous (Fleming, 2001; Tushman and Anderson, 1986). Because the potential of certain technological developments is unclear in an uncertain market, other firms may become less certain about the value of the technology skills, prospects of commercialization of the technology, and the learning ability possessed by the focal firm in future alliances. Potential alliance partners will doubt the usefulness of the inventive capabilities that the focal firm has for future alliances (Ndofor and Levitas, 2004). Similarly, with a higher degree of firm-specific uncertainty, the value of a firm's inventive capabilities can become questionable since other firms will have difficulties understanding the overall impact of the inventive capabilities on the focal firm's future performance and its potential as an alliance partner. The doubts other firms have about the value of the firm's inventive capabilities should be higher when the firm faces a high level of firm-specific uncertainty. Therefore, other firms are less likely to perceive the inventive capabilities of the focal firm as a reliable signal under increased environmental and firm-specific uncertainty.

Second, because of the ambiguous value of a firm's inventive capabilities and innovative technologies under high uncertainty, the cost of inferring and verifying the value of a firm's inventive capabilities for future alliances will also increase for other firms. Firms need to expend extra time and effort to scan the task environment, analyze relevant information, and distill useful information from various sources. When market uncertainty is high, such search activities will involve more difficulties (Venezia, 1980). Furthermore, to infer the value of the signals related to inventive capabilities, potential partners have to invest resources to acquire certain knowledge in relevant technological areas. Such investments become more risky when the parties face a higher level of market uncertainty (Tushman and Anderson, 1986). This logic also applies to the uncertainty surrounding a focal firm's internal conditions. When the level of firm-specific uncertainty is high, the potential partners will have to expend more resources to determine the value of the capabilities.

Based on the above arguments, we propose the following hypotheses:

Hypothesis 4. The effect of inventive capabilities (strength and focus) on R&D alliance formation is weaker when market uncertainty is high.

Hypothesis 5. The effect of inventive capabilities (strength and focus) on R&D alliance formation is weaker when firm-specific uncertainty is high.

In contrast, we argue that under a higher level of uncertainty, the signaling effect of the quality of a firm's board interlocks will become stronger. When the inventive capabilities as a signal lose their informational power, other firms will rely more on alternative signals in their assessments. In this case, relational ties (board interlocks in our context) serve as the alternative. Prior research suggests that network ties are important sources of information in alliance formation under high degrees of uncertainty (Li et al., 2008). Janney and Folta (2006) revealed that the impact of relationships on a firm's ability to attract capital became stronger when the uncertainty about the firm's future prospects was high. Given the reduced reliability of a firm's inventive capability as a signal, network quality can be a dependable alternative under high levels of uncertainty. Gulati et al.

(2009) found that with increased firm-specific uncertainty, connections to certain partners help establish investors' confidence in the capacity of a firm to extract benefits from forming new alliances. Therefore, albeit the heightened level of market and firm-specific uncertainty, interfirm relational ties, and in particular, board interlocks, remain largely reliable.

At the same time, relative to the increased cost of analyzing the value of a firm's inventive capabilities, the cost of inferring the quality of a firm's board interlocks under high levels of uncertainty is likely lower. For instance, information on board members is normally publicly available, and firms can easily access background information on the directors of a firm's board to evaluate the quality of a firm's network ties. Furthermore, firms do not need to invest extra resources to decipher the signals of network quality. Since firms are more likely to search for information and look for cues in places where the relative cost is lower (Cyert and March, 1963), under high uncertainty, firms are likely to rely on board interlock ties for information given the relatively lower cost involved.

Finally, under the situation where firms in the market have difficulties foreseeing the future, they are more likely to value any information that may help them better prepare for the future. The perception that high-quality board interlocks could be valuable information beneficial to a firm's decision-making process is thus strengthened under a higher level of uncertainty.

Therefore, as the signaling power of inventive capabilities is weakened, board interlock ties can become a more viable channel through which firms can look for social cues and make inferences about a firm's potential quality and reliability as a partner. That is, with increased market and firm-specific uncertainty, other firms will pay more attention to the focal firm's connections through its board and less attention to its internal inventive capabilities. Consequently, others are more likely to rely on the quality of a firm's board interlocks as the signal to make judgments. Thus, it is likely that when firms face high levels of uncertainty, the signaling effect of the quality of a firm's board interlock ties becomes stronger. We thus posit,

Hypothesis 6. The effect of the quality of a firm's board interlocks on R&D alliance formation is stronger when market uncertainty is high.

Hypothesis 7. The effect of the quality of a firm's board interlocks on R&D alliance formation is stronger when firm-specific uncertainty is high.

Method

Sample

Our sample covers 207 companies in the US biotechnology industry that were founded between 1990 and 2003. We chose biotechnology companies because of the strong presence of both inventions and alliances in this industry (Gopalakrishnan et al., 2008). We traced the entire history of invention and alliance activities of all sample firms in detail since their founding. As a result, the data structure in this study is an unbalanced panel (pooled cross-sectional and time series data).

The companies were selected from the BioScan database, which contains the most updated information on firms in the biotechnology industry and has been used in prior research (Powell et al., 1996). This database also provides information on various aspects of the firms, including the alliances formed by each firm since its founding date, a firm's products, merger and acquisition activities, founding date, and so on. We also verified the alliance information with the Joint Ventures and Strategic Alliances database compiled by Thomson's Securities Data Company (SDC), adding any additional alliance information available. We included only public firms in this

study since information on the board of directors and financial performance is available only for public firms. After deleting the firms with missing values, our sample includes 2039 firm-year observations.

Dependent variable

To generate our dependent variable, we first counted the total number of R&D alliances formed by a firm in a particular year. As most of the firms in our sample (98.09%) formed fewer than two R&D alliances in one particular year, a binary variable indicating whether an R&D alliance was formed in a particular year was used as the dependent variable, with 1 indicating the formation of an R&D alliance and 0 otherwise. We included both joint ventures and contractual alliances in our sample because our theories do not differentiate between the different types of alliances.

Independent variables

This study considers two independent variables: the board interlock quality and inventive capabilities of a firm. To measure *board interlock quality*, following previous studies (Sullivan et al., 2007; Westphal and Khanna, 2003), we looked to see whether the focal firm is connected through board interlocks to large firms and better performing firms and whether the board members are connected to other firms. Information on boards of directors and their network connections was collected from the proxy statements that firms file with the US Securities and Exchange Commission (SEC). We obtained yearly interlock information for 1990–1999 from proxy statements of the sampled firms.

The size and performance of the partner firms were used as indicators for board interlock quality in prior studies as large and better performing firms should be more legitimate in their fields (Sullivan et al., 2007). Board members with more connections to other firms are more resourceful in terms of acquiring information and may be perceived as better able to provide good governance to firms. Different from some previous studies (e.g. Westphal and Khanna, 2003), we did not include the education levels of the board members since the information was missing for a majority of the board members in our data. We collected data on sales and return on assets (ROA) for the focal firm's network partners, as well as data on the number of board members who sat on more than one board other than the focal firm's board. The three variables loaded on one factor, with loadings of 0.60 or greater on the same factor and less than 0.30 on the other factors. Cronbach's alpha was about 0.70, indicating an acceptable level of reliability (Nunnally, 1978). We then created a composite measure of network quality based on the factor loading coefficients from a factor analysis of the three variables, relying on the iterated principal factors method. The network quality measure was constructed using the information of the three variables for the prior year.

Following earlier studies (Fleming, 2001; Glismann and Horn, 1988; Lavie et al., 2007; Stuart, 1998), we used the focal firm's patent activities to measure a firm's inventive capabilities because "patents identify inventions" (Stuart and Podolny, 1996: 21). Patenting activities are common in biotech industry and have been explored in prior research (Owen-Smith and Powell, 2004; Whittington et al., 2009). We collected patent data from the LexisNexis patent database for all firms in our sample since their founding. The accumulated number of patents since a firm's founding, weighted by the subsequent citations by others, was used to indicate a firm's *strength of inventive capabilities*.[1] As the value of this indicator is highly skewed, we took its square root as the measure. A firm's *focus of inventive capabilities* was constructed as follows. First, we calculated

the entropy-based score (Ancona and Caldwell, 1992) $E = -\sum_{i=1}^{n} P_{ij} \ln P_{ij}$, where i is the patent class and P_{ij} is the proportion of the occurrence of i over the total number of patent classes for all of focal firm j's citations in its prior patents. Based on the technological components in each patent, patents were categorized into about 400 patent classes by the patent office (Trajtenberg et al., 1997). Second, we obtained the score for *focus of inventive capabilities*, $\max(E) - E$, by reverse coding the entropy-based score. If this score is high, the focal firm is more focused on certain technological components for its invention activities.[2]

Moderating variables

In this study, we examine uncertainty as the moderating variable. Following prior research on the impact of uncertainty on alliance formation (Beckman et al., 2004), we focus on two dimensions of uncertainty based on its origin: market uncertainty and firm-specific uncertainty.

We used the volatility of stock prices as a measure of uncertainty; this measure has been commonly used in prior research (Leblebici and Salancik, 1981). As Lang and Lockhart (1990: 110) pointed out, "… volatility is positively related to firm managers' perception of uncertainty and therefore reflects phenomena that affect decision making." Following Beckman et al. (2004) as well as Gulati et al. (2009), *firm-specific uncertainty* was measured by the standardized monthly volatility of the focal firm's stock price in the year prior to the formation of an alliance. The monthly volatility was calculated as the coefficient of variation in firm j's monthly stock closing price during a particular year. We used the following formula for the measure: σ_{ij} / μ_{ij}, where σ_{ij} represents the standard deviation of firm j's monthly closing price in year i, and μ_{ij} is firm j's mean monthly closing price in year i. We acquired the monthly stock price data from Compustat and from the Center for Research in Security Prices (CRSP) when Compustat data were unavailable. *Market uncertainty* was measured by the mean monthly stock price volatility of all sampled firms in the focal firm's industry group defined by the 4-digit Standard Industrial Classification (SIC) code in the year prior to the alliance formation (Beckman et al., 2004). A greater volatility of the stock prices of firms in a firm's industry group implies a higher level of environmental uncertainty.

Control variables

We controlled for a few variables that might affect our dependent variable, the likelihood of forming alliances, through their impact on a firm's incentives to form alliances with others. This can increase our confidence in the signaling effect of our independent variables.

We controlled for *firm age, size* (measured by the natural logarithm of firm sales), and *performance* (measured by ROA). By controlling for firm performance, we could also ease the concern that firm-specific uncertainty may be related to firm performance. The information on firm age was based on firm founding year indicated in the BioScan database. The firm's sales and ROA data were collected from the Compustat database.

We included a dummy variable indicating whether the focal firm had prior alliances with current partners. As repeated interactions can be a proxy for trustworthiness (Dyer and Singh, 1998), by including this measure, we controlled for the "trust" dimension coming from network ties and the possibility that the choice of repeated ties might be directly related to the level of uncertainty. This control may also account for the potential inertia in alliance partner selection (Li and Rowley, 2002). We controlled for the total number of board interlock network ties since the number of ties

can give firms information advantages that could affect the attractiveness of the firm to others (Gould, 2002).

It is also important to control for a firm's knowledge complementarity as one of the important motivations for building alliances is to acquire complementary knowledge (Rothaermel, 2001). Therefore, we controlled for a firm's range of product areas by counting the number of patent classes for a firm in a year because the more product areas a firm spans, the more likely it is that the firm's knowledge complements others' knowledge (Rothaermel and Boeker, 2008). We further controlled for firm slack, measured by the reverse-coded debt ratio (Greve, 2003).

Patent generality indicates the degree to which a patent can be applicable to other firms (Hall et al., 2005; Trajtenberg et al., 1997). We controlled for average patent generality by calculating the average of generality of all patents in the prior year. The generality of each patent was calculated as the percentage of citations received by a focal patent in a particular patent class over the total number of patent classes, a formula adopted from Trajtenberg et al. (1997). The correlation between capability focus and generality in this study is very low (0.063), suggesting that the two variables likely measure different aspects of patent activities.[3]

Finally, we controlled for the unobservable industry effect for each firm by adding a set of dummy variables indicating 4-digit SIC categories.

Model specification

Since the dependent variable is a binary variable, coded as "1" or "0," the data in this study included repeated observations for each firm across different years, and the industry category (4-digit SIC code) was constant across the time period for a firm, we used random-effect logit models to estimate the coefficients: $\text{logit}[P(y_{it})] = \alpha + \beta x_{it} + \varepsilon_{it}$, where ε_{it} represents the random error.

Endogeneity check

As the observed relationships may be due to some unobservable factors, it was necessary to check for possible endogenous relationships between a firm's inventive capabilities and R&D alliance formation. For example, some firm-specific characteristics and external factors can drive both the level of inventive capabilities and the likelihood of forming an R&D alliance. To address this issue, we included important firm-level characteristic variables and industry dummies in all models. We also conducted a Hausman test using the firm's R&D intensity, measured by the ratio of a firm's total R&D expenditures to its total assets in a year, as the instrument variable. R&D intensity was selected because R&D expenditure has a significant impact on the formation of R&D alliances (Lavie and Rosenkopf, 2006). R&D intensity data were collected from the Compustat database. The Hausman test failed to reject the null hypothesis, indicating that endogeneity should not be a concern in this study (Hausman, 1978).

Results

Table 1 presents descriptive statistics and pairwise correlation coefficients for the key study variables. The correlations among the independent variables used in the models do not appear to be particularly high. Market uncertainty was found to have a significant impact on the reinforcing of board interlocks (Beckman et al., 2004). The low correlation of the uncertainty variables with board interlock quality in our study, however, indicates that multicollinearity is not a concern for our analyses. A further inspection of the correlations does not reveal any multicollinearity concern

Table 1. Descriptive statistics and correlations for key study variables.

Variable	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. R&D alliance formation	0.10	0.30														
2. Firm age	5.04	3.47	0.11													
3. Firm size	−0.94	6.00	0.10	0.15												
4. Firm performance	−1.40	4.93	0.03	0.11	0.08											
5. Prior cumulated R&D alliances	0.38	0.84	0.20	0.38	0.11	0.06										
6. Whether prior ties	0.01	0.11	0.16	0.02	0.02	0.01	0.03									
7. Total ties	19.88	5.51	0.02	−0.01	−0.04	0.01	0.03	0.02								
8. Product areas	6.70	3.87	0.11	−0.01	0.13	0.05	0.02	0.04	−0.01							
9. Generality	0.25	0.08	−0.23	−0.10	−0.09	−0.03	−0.07	−0.08	0.01	−0.06						
10. Firm slack	−0.01	1.57	0.03	−0.01	0.01	0.01	0.00	0.03	0.01	0.05	−0.01					
11. Market uncertainty	0.31	0.07	0.11	0.61	0.08	0.06	0.36	−0.01	−0.00	0.03	−0.09	−0.05				
12. Firm-specific uncertainty	0.32	0.14	−0.01	0.08	−0.03	−0.13	0.02	−0.01	0.05	−0.01	0.00	−0.02	0.20			
13. Strength of inventive capability	1.70	0.74	0.10	0.77	0.14	0.13	0.31	0.00	−0.02	−0.01	−0.10	0.01	0.45	0.02		
14. Focus of inventive capability	1.22	0.24	0.08	0.01	−0.09	−0.02	−0.02	−0.01	−0.03	−0.01	−0.06	0.01	−0.01	−0.02	−0.09	
15. Board interlock quality	−0.01	0.22	0.10	−0.02	0.03	0.01	0.06	0.03	−0.07	−0.02	0.02	0.01	−0.01	−0.03	0.01	0.04

R&D: research and development; SD: standard deviation.
Correlations with a magnitude greater than 0.05 are significant at $p < 0.05$ level.

for any variables either. The mean variance inflation factor (VIF) is 1.18, and the maximum VIF is 1.71. To avoid possible collinearity issues in models involving interaction terms, we centered the variables involved in the interaction terms by subtracting the mean from each variable before we entered the variables into the regressions (Aiken and West, 1991).

Table 2 presents the main results of the logit model estimations. As shown in Model 1, the impact of board interlock quality was positive and significant ($p < .01$), consistent with Hypothesis 1 stating that firms with high-quality board interlocks are more likely to form R&D alliances with other firms. The effects of the strength and focus of inventive capabilities were both positive and significant ($p < .01$ and $p < .001$, respectively). Therefore, Hypotheses 2 and 3, stating that firms that have strong inventive capabilities and more focused inventive capabilities are more likely to form R&D alliances with other firms, are both supported.

In Model 2 reported in Table 2, we added the interaction terms of the strength of inventive capabilities with market uncertainty as well as firm-specific uncertainty to test Hypotheses 4 and 5. The results show that the interactions between the strength of inventive capabilities and market uncertainty as well as firm-specific uncertainty were both negative and significant ($p < .05$ and $p < .01$, respectively). This indicates that the positive impact of the strength of a firm's inventive capabilities on R&D alliance formation was weaker under a high degree of market and firm-specific uncertainty. However, as shown in Model 3 of Table 2, the interaction between the focus of inventive capabilities and market uncertainty was positive and significant ($p < .05$) and the interaction with firm-specific uncertainty was not significant, contrary to our Hypotheses 4 and 5. Therefore, the parts of Hypotheses 4 and 5 regarding the strength of inventive capabilities are supported, but the parts regarding the focus of inventive capabilities are not. The revealed interaction effects between the focus of inventive capabilities and uncertainty deserve further exploration in future research. For now, they seem to suggest that the desire of the other firms for evaluation clarity and consensus can be even stronger under uncertainty, and consequently, firms with non-focused inventive activities are more likely to be dismissed under uncertainty.

Model 4 presents the interaction effects of board interlock quality with uncertainty. The results suggest that both market uncertainty and firm-specific uncertainty strengthen the positive effect of network quality on R&D alliance formation ($p < .001$). Therefore, Hypotheses 6 and 7 are strongly supported.

Model 5 included all the interaction terms, and the results are generally consistent with the results from the earlier models.

In summary, we have found general support for our predictions about the main effects of board interlock quality and inventive capabilities on alliance formation: the quality of board interlock ties and the quality of inventive capabilities (both strength and focus) have a positive effect on R&D alliance formation. We have further found that under higher levels of uncertainty, the impact of the strength of inventive capabilities will weaken while the impact of network quality will strengthen.

Supplementary analysis

In order to check the robustness of our measure of board interlock quality, we performed supplementary analyses by using a Bonacich eigenvector (Podolny, 1993) to indicate the tie quality of the focal firm.

Bonacich eigenvectors have been widely used in prior studies as a measure of network status (Podolny, 2001), based on the assumption that firms have a high status if they are connected to other high-status firms (Podolny, 1993). Therefore, this measure essentially indicates the status and thus the legitimacy of those firms that the focal firm is connected to. To generate this alternative

Table 2. Random-effect logit estimates of R&D alliance formation.

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
Firm age	.014 (.047)	.006 (.040)	.017 (.048)	.009 (.046)	.004 (.045)
Firm size	.034* (.017)	.034* (.017)	.033 (.018)	.034 (.018)	.034 (.018)
Firm performance	−.008 (.021)	−.008 (.020)	−.011 (.020)	−.012 (.020)	−.015 (.020)
Prior cumulated R&D alliances	.283 (.231)	.315 (.169)	.263 (.222)	.285 (.200)	.291 (.190)
Whether prior ties	1.985*** (.490)	2.029*** (.488)	1.923*** (.489)	2.022*** (.508)	2.034*** (.506)
Total ties	.033 (.018)	.031 (.017)	.035 (.018)	.037* (.019)	.037* (.019)
Product areas	.065** (.023)	.061** (.023)	.068** (.024)	.068** (.025)	.066** (.025)
Generality	−11.135*** (1.390)	−11.196*** (1.293)	−11.802*** (1.429)	−11.677*** (1.410)	−12.439*** (1.474)
Firm slack	.073 (.107)	.068 (.104)	.082 (.116)	.070 (.109)	.067 (.109)
Market uncertainty	4.192* (1.636)	4.293** (1.641)	4.087* (1.661)	4.744** (1.678)	4.637** (1.713)
Firm-specific uncertainty	−.343 (.589)	−.518 (.602)	−.763 (.654)	−.517 (.636)	−.995 (.700)
Board interlock quality	.989** (.393)	1.007** (.397)	.957** (.383)	2.577*** (.523)	2.571*** (.528)
Strength of inventive capability	.287** (.095)	.089 (.108)	.249** (.095)	.289*** (.095)	.106 (.115)
Focus of inventive capability	1.905*** (.344)	1.933*** (.339)	2.222*** (.366)	1.917*** (.354)	2.231*** (.379)
Strength of capability × market uncertainty		−2.086* (1.240)			−1.097 (1.350)
Strength of capability × firm-specific uncertainty		−4.110** (1.654)			−4.728** (1.807)
Focus of capability × market uncertainty			16.081** (6.160)		17.002** (6.730)
Focus of capability × firm-specific uncertainty			3.866 (2.362)		1.719 (2.702)
Interlock quality × market uncertainty				18.784*** (5.708)	18.091*** (5.796)
Interlock quality × firm-specific uncertainty				11.836*** (3.033)	12.972*** (3.056)
Industry dummy	Yes	Yes	Yes	Yes	Yes
Constant	.430 (1.029)	.714 (.998)	1.007 (1.061)	.338 (1.116)	1.129 (1.125)
N	2,039	2,039	2,039	2,039	2,039
Wald chi-square	204.11***	211.31***	210.24***	206.23***	216.22***

R&D: research and development.
***p < .001, **p < .01, *p < .05 (one-tailed test for hypothesis testing, two-tailed test for others).

Table 3. Supplementary analyses using the Bonacich eigenvector as an alternative measure of network quality.

Variable	Model 6	Model 7
Firm age	.034 (.051)	.041 (.052)
Firm size	.037* (.018)	.036 (.019)
Firm performance	−.009 (.021)	−.010 (.021)
Prior cumulated R&D alliances	.103 (.211)	.077 (.206)
Whether prior ties	2.028*** (.508)	1.971*** (.513)
Total ties	.060** (.023)	.064** (.024)
Product areas	.061* (.027)	.060* (.028)
Generality	−11.738*** (1.387)	−11.791*** (1.400)
Firm slack	.055 (.099)	.047 (.094)
Market uncertainty	4.729** (1.724)	4.682** (1.757)
Firm-specific uncertainty	−.409 (.612)	−.541 (.650)
Strength of inventive capability	.329*** (.101)	.329*** (.103)
Focus of inventive capability	1.935*** (.365)	1.868*** (.370)
Bonacich eigenvector	.036*** (.009)	.035** (.012)
Bonacich eigenvector × market uncertainty		.185 (.138)
Bonacich eigenvector × firm-specific uncertainty		.145* (.080)
Industry dummy	Yes	Yes
Constant	−.146 (1.233)	−.186 (1.283)
N	2,039	2,039
Wald chi-square	182.27***	174.83***

R&D: research and development.
***p < .001, **p < .01, *p < .05 (one-tailed test for hypothesis testing, two-tailed test for others).

network quality variable, we constructed an adjacency matrix representing the board interlock ties among the studied firms. We coded the matrix with a "1" indicating that two firms were tied and a "0" indicating that they were not. We then calculated the Bonacich eigenvector (Bonacich, 1987), which is formally stated as $s(\alpha,\beta)=\alpha\sum_{k=0}^{\infty}\beta^{k}\mathbf{R}^{k+1}\mathbf{1}$, where α is a scaling factor, $\mathbf{R}$ is the network matrix, β is a weighting parameter that can range between zero and the absolute value of the inverse of the value of the maximum eigenvalue of the network matrix, and $\mathbf{1}$ is a column vector where each element has the value "1." The Bonacich eigenvector is also a column vector in which each element denotes the network quality (status) of a firm in our sample in a particular year. This was computed using the UCINET VI software package (Borgatti et al., 2002).

Table 3 presents the results relying on the alternative measure of interlock network quality. The results are consistent with the earlier findings. Specifically, in Model 6, the main effect of the Bonacich eigenvector was positive and significant ($p < .001$), consistent with the argument about the positive impact of network quality. In Model 7, the interaction term of the Bonacich eigenvector and firm-specific uncertainty was positive and significant ($p < .05$). Although the interaction between the Bonacich eigenvector and market uncertainty was positive, it was not significant. We further conducted a split sample analysis and found that when market uncertainty is high (above the median), the effect of the Bonacich eigenvector is positive and significant ($p < .01$, two-tailed test); in contrast, when market uncertainty is below the median, such an effect becomes nonsignificant. Generally, these findings provided by the supplementary

analysis suggest that the earlier findings based on our initial network quality measure are robust.

Discussion

Extending our understanding of how board interlocks can serve as "prisms" providing informational cues about the focal firm's quality to other firms in the process of R&D alliance formation, our study suggests that the quality of a firm's board interlocks can serve as a signal for other firms to assess its state of governance. In particular, firms with high-quality board interlocks are more attractive to other firms as an R&D alliance partner. Importantly, we also found evidence that under high levels of both market and firm-specific uncertainty, firms tend to look at cues derived from board interlocks rather than those from a firm's inventive capabilities to reduce partnership risks. Our study contributes to the literature by revealing important boundary conditions that affect the influences of inventive capabilities and board interlock quality as signals for a firm's quality as an R&D alliance partner. It suggests that in the process of alliance partner selection, firms could shift their attention to certain signals about the focal firm depending on particular contingent factors.

Our study has important contributions to the literature on board interlocks and corporate governance. Research on board interlocks has largely focused on the function of the interlocks as an information channel through which managerial practices are diffused (Coles et al., 2008; Davis, 1991; Haunschild, 1993). The research on the role of board interlocks as a "prism" providing informational cues about the focal firm, however, is limited mainly due to difficulties in empirical testing (Mizruchi, 1996). Our study, therefore, is a useful attempt at demonstrating the signaling function of board interlocks.

This study also makes valuable contributions to the research of corporate governance. While the extant literature focuses on the impact of board interlocks on the monitoring and advisory role of the board (Hwang and Kim, 2009; Larcker et al., 2005), our study suggests that the quality of a firm's board interlock ties enables other firms to make inference about the quality of its top management.

Although we have examined the possible endogeneity issue, certain concerns about endogeneity might still remain. For instance, the association between the board interlocks and alliance formation might be caused by some unobservable quality dimensions. This concern, however, can be eased by the fact that in addition to our endogeneity test, we have included a substantial number of control variables that might affect the firm quality in our models and therefore left limited room for the possibility that unobserved causal factors affecting the outcomes. It is also difficult to explain how the unobserved common factors would have a differential effect as uncertainty changes.

One might reasonably suspect that a firm's inventive capabilities could be a direct function of its network ties. In our particular context, the correlation between inventive capabilities (both strength and focus) and network quality is quite low (0.01 and 0.04, respectively), and further analysis that treated inventive capabilities as the mediating variable between board interlock quality and R&D alliance formation failed to support any such effect. Therefore, at least in our context, inventive capabilities of firms are less likely to be a direct function of the quality of network partners.

An important note about our finding regarding the relationship between board interlock quality and the likelihood of R&D alliance formation is that given our particular context and measurements, the relationship we found is less likely to be influenced by reverse causality. First, as we have used the board interlocks as our network quality measure, it would be difficult to argue that the formation of R&D alliances will directly increase the quality of board interlock ties. Second,

we have included a control variable, the total number of existing prior R&D alliances, in the models. With this control variable, we can effectively show how, given the same number of alliance partners, the quality of board interlock ties affects the development of current alliances. Third, our use of lagged interlock quality to predict the current alliance formation rate can greatly ease our concerns about reverse causality.

Theoretical implications

Our results have implications for studies of uncertainty and theories of interfirm networks in general as board interlocks are often used as indicators of firm networks (Mizruchi, 1996).

First, it is important for us to note that network prominence becomes even more important under high levels of uncertainty in the process of R&D alliance formation. Considering another finding from this study that the total number of board interlock ties has a positive effect on the formation of R&D alliances (Model 5), it is possible that network expansion (more connections) and exclusion (prominent firms only connect to other prominent firms) are not always at odds in terms of helping firms cope with uncertainties in the process of alliance formation. While we did not specifically examine whether and how the number of network ties a firm has can help it in the process of R&D alliance formation, an important and intriguing implication is that the tension between network expansion and exclusion, which is an important issue in the studies of networks (Podolny, 2001), might be moderated by the types of strategic actions a firm is involved in. For certain actions, such as forming alliances, network expansion and exclusion might in fact complement each other.

Second, this study explicitly differentiates between two dimensions of a firm's inventive capabilities, strength and focus. Previous research has focused on the dimension of strength (Khilji et al., 2006; Stuart and Podolny, 1996). Our findings show that the two dimensions have different impacts on R&D alliance formation under uncertainty: while the impact of inventive capability strength becomes weaker under increased levels of both market and firm-specific uncertainty, the impact of inventive capability focus becomes stronger. These findings suggest the importance of how other firms perceive and evaluate different signals from the focal firm and may inspire researchers to examine how the perception and evaluation process of other firms ensures certain facets of firm capabilities to be more visible signals under particular conditions.

Managerial implications

This study also has important implications for managers. Our study suggests that since managerial attention and time are scarce resources (Cyert and March, 1963), managers can more effectively allocate their time and attention to mechanisms facilitating the formation of strategic alliances by identifying circumstances under which the different factors would have different impacts. Our study provides an important understanding for managers of how firms might allocate their limited resources to form R&D alliances under uncertainty.

In particular, our findings highlight the importance of high-quality network ties for managers in building alliances under high levels of uncertainty. Firms looking to build R&D alliances under high levels of uncertainty must rely more on existing prominent ties or make an effort to acquire more prominent ties, such as selecting prominent board members (Westphal and Khanna, 2003). Our findings also suggest to managers that putting efforts into diversifying capabilities does not necessarily pay off if they are hoping to form alliances with other firms. It is important for

managers of the focal firm to project a clear image of who the firm is and what the firm is good at to potential partner firms.

In addition, the findings on the positive effect of the strength and focus of inventive capabilities on R&D alliance formation suggest that in order to be more positively perceived by potential partners, firms' top managers not only need to invest in developing a strong capability to invent, they also need to invest in a consistent and focused manner. Firms might need to strike a balance between the strength of the inventive capability and the focus of such capability.

Limitations and future research directions

The findings presented here need to be interpreted in the light of their limitations, and future improvements are possible. First, as we only used publically traded firms in our sample for data availability reasons, one might question whether our findings can be generalized to privately held firms. Although much of the information in this study, such as financial performance or board interlocks, is more readily available for publically traded firms, the arguments we propose in the study are not specific to public firms. The effects found in this study, however, need to be confirmed with privately held firms in future research. Another issue related to the generalization of this study is that the biotech industry has changed much since the time period examined in this study. Our sample period represents a golden time for a booming industry, which today is facing multiple challenges such as a reduced federal budget, increased difficulties in attracting finance for early-stage research, and tough time to recoup from the costly development for new drugs due to insurance and other barriers. Under the current circumstances, R&D collaborations are even more imperative. Young firms in this industry could face even more difficulties in forming alliances with others. Consequently, signals about the focal firm could matter more. In other words, our findings regarding the role of board interlocks could be even more relevant for young firms in today's biotech industry.

Second, while stock market volatility has been utilized in prior research on uncertainty (Beckman et al., 2004; Gulati et al., 2009), researchers have also developed other ways to measure uncertainty (Keats and Hitt, 1988). While our study provides a first step to test the impact of uncertainty as a boundary condition in differentiating between the signaling effects of firm inventive capabilities and board interlock quality, future studies can benefit from more refined analyses. For example, the construct of market uncertainty might reflect only one dimension of environmental uncertainty (Milliken, 1987). Future studies could also consider the impact of different types of environmental uncertainty, such as technology and competitive uncertainty, in the process of forming alliances and how different network properties help or hinder firms in forming alliances with others under such uncertainties. Firms could potentially rely on either the information or status benefits of the focal firm's network ties, depending on the type of environmental uncertainty. That is, it is possible that uncertainty about financial performance is somehow different from uncertainty about technology performance, and consequently, firms use different strategies to cope. Future research could confirm our finding based on different types of environmental uncertainty to firms.[4]

Third, future research could also examine whether firms' response to uncertainty may depend on the characteristics of their top management teams. One salient factor might be the prominence of the firm's top management team since managers not only attract other firms' attention but also increase other firms' confidence in the quality of the inventions. A reputable management team can act as a good signal to other firms, and it might be more important under high uncertainty. The management team can reduce the perceived risk level associated with particular inventions due to an increased level of confidence in the firm's ability to select and implement a certain technology

trajectory. Under a high level of uncertainty, the impact of the prominence of top management teams might be greater while the impact of inventive capabilities might decline. Future research in this area could address these questions.

Fourth, due to data availability and scope of the article, we were not able to examine how different types of alliances might be affected under uncertainty. For instance, joint ventures may require more commitment from each party and thus suggest greater risks than other forms of alliances do. It is possible that under increased uncertainty, it will be even more costly for firms to validate information from a focal firm's inventive capability, and firms might be even less likely to rely on that signal in the formation of joint ventures. As prior study shows that alliances could differ in terms of their nature (Rothaermel and Deeds, 2004), it is possible that the impact of uncertainty may differ for explorative versus exploitative alliances: alliances with universities might rely on different signals than alliances with downstream pharmaceutical firms for exploitations. Future research in this direction would be useful.

In addition, future research might examine the signaling effect of different types of interfirm network ties, since different network ties may imply different motivations. For instance, direct network ties might have a stronger impact than do indirect ties because other firms might assume that there is a close relationship between direct network ties and the focal firm and that these direct network ties might exert more influence on the focal firm's decision-making process. It is also possible that under certain circumstances, firms are more concerned with immediate gains than they are with long-term performance. For example, a closer relationship between partners may imply a motivation for long-term rather than short-term gains, and under such situations, entering a "learning race" may be less likely (Hamel, 1991).

While it is likely that biotech firms engage in the R&D over a range of products and technologies in different time periods, our data set contains a fair number of biotech firms that engaged in the R&D of drug-related products or technologies specifically. The data set was only used to explore certain theoretical mechanisms that could result under certain circumstances. The mechanisms we revealed could be very much relevant to many young firms in knowledge-intensive industries, independent of the time period of the data set. For instance, Powell et al. (1996) used a data set in an earlier time period, but the mechanism of learning networks revealed in their study is still very much relevant for many firms, including biotech firms, today.

On a final note, as the structural nature of interlock relationships might predict network inertia, future research can benefit from a detailed examination of the impact of the stability of board interlocks on the choice of future alliance partners. Board interlocks tend to be relatively stable over time (Davis et al., 2003; Mizruchi, 1992), but changes can also happen (Sullivan et al., 2007). Their stability might suggest that firms are more likely to select the same partners over the years under influences of the board. However, the fact that firms can change decisions and choices due to social and institutional forces also suggests the possibility that firms might be flexible in choosing partners under influences of the board. In our current context, board members are likely to understand the importance of quick adaptation in a dynamic environment, and it is possible that even the stability of board interlocks does not ensure alliance formation with prior partners.

Conclusion

This study provides empirical evidence on how firms rely on the board interlocks to make inferences about the focal firm's quality as an R&D alliance partner and how such a signaling effect may change in light of other signals such as inventive capability from the firm under market and firm-specific uncertainty. We show that firms in general are more likely to form R&D alliances

with firms with higher board interlock quality and stronger as well as more focused inventive capabilities. We also show that firms tend to rely more on cues regarding the focal firm's interlock quality and less on cues regarding its inventive capability when either market uncertainty or firm-specific uncertainty is high. The main reason for this finding is that the value of the technological capability becomes highly ambiguous and the cost of verifying this value rises under higher levels of market and firm-specific uncertainty.

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Notes

1. In our robust analysis, we also used the non-weighted accumulated number of patents and the average number of patents in prior years as a measure of the strength of inventive capabilities, and the results were consistent with those reported here.
2. Our focus measure is different from those in other studies using patent data. For instance, Katila and Ahuja (2002) used new citations to measure search scope, and Rosenkopf and Nerkar (2001) used self-citations to capture the extent of exploration.
3. The correlation was low even when the two variables were constructed with the same time window.
4. While Beckman et al. (2004) found that neither market nor firm-specific uncertainty has significant effects on the broadening of alliance ties, our results reveal that the main effect of market uncertainty on alliance formation was significant and positive. This disagreement might be due to the fact that while Beckman et al. (2004) focused on the broadening of new alliance ties, we focused on the general formation of network ties. We thank one anonymous reviewer for pointing out this important issue.

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Author biographies

Bilian Ni Sullivan is an associate professor in the Department of Managment, Hong Kong University of Science and Technology. She received her Ph.D from the Graduate School of Business, Stanford University. Bilian's research covers topics in the area of organization theories and has been published in Administrative Science Quarterly, Organization Science and other journals.

Yi Tang is an assistant professor in the Department of Management and Marketing, Hong Kong Polytechnic University. He received his PhD from the Department of management, Hong Kong University of Science and Technology. Yi's research has been published in Academy of Management Journal, Strategic Management Journal, Journal of Management, and among others.