# R&D Partner's Network Position and Focal Firm's Innovation Performance: A Knowledge Spill-In Perspective

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***Abstract*—Research and development (R&D) collaboration is an important source of innovation. Network researchers have identified the importance of network resources in a firm's innovation performance. However, previous studies have largely focused on the ego network (i.e., a firm's own network position). In this study, we adopt an alter network perspective and explore how the network position of a firm's alter (i.e., R&D partner) influences the focal firm's innovation process. Drawing upon social capital theory and the knowledge-based view, we argue that R&D partners' superior network positions (e.g., structural holes and centrality) provide second-order social capital, and positively influence a firm's innovation performance through increased knowledge spill-in (or incoming knowledge spillover). We also find that relationship duration between firms and R&D partners moderates the relationship between R&D network positions and knowledge spill-in in an inverted U-shape. This study highlights the impact of second-order social capital on a firm's innovation process from a knowledge-based view. We suggest that firms leverage both direct and indirect network resources and consider the dynamics in their R&D partnerships to facilitate better knowledge flows in the focal firms.**

***Index Terms*— R&D partners, network position, knowledge spill-in, relationship duration, second-order social capital**

## I. INTRODUCTION

THE knowledge-based view suggests that one of the key motivations for firms to seek R&D partnerships is to gain knowledge resources [1]. Despite concerns related to knowledge leakage and misappropriation, the combination of internal R&D and external knowledge has been found to have a positive impact on a firm's innovation performance [2]. Through continuous knowledge flows in R&D networks, firms can gain access to an enlarged external knowledge pool, a process which ultimately increases their knowledge stocks [3]. Knowledge spillovers in R&D networks provide opportunities for firms to complement each other's internal knowledge base and benefit from specialization through collaboration [4]. Although the relationship between knowledge benefits and a firm's intentions to seek R&D collaboration has been well-established [1], [5], very few research studies have provided a nuanced understanding of how and when firms are more likely to benefit from knowledge spill-in for firm innovation [6], [7]. Oldroyd and Gulati [8] have defined inter-organizational *knowledge spill-in* as the knowledge that is passed on from one organization to another organization. Other researchers use the terms *incoming knowledge spillovers* [9], [10] or *knowledge inflow* [11] interchangeably. Bernal, et al. [12] highlights the need for a better understanding of how knowledge flows in R&D partnerships and how they influence the dynamics of collaboration for innovation.

One of the theoretical approaches is to use social network and social capital theory to understand knowledge flows in R&D partnerships. Pioneering scholars have suggested that by participating in inter-firm networks, a firm can obtain and share valuable information [13]. The network ties established between firms and the social structures of network actors create social capital [14]. A firm's positions in the structure of exchange bring competitive advantages and can be considered as an asset in its own right [15]. There are two network perspectives typically used to study inter-firm networks. The first, the "ego" network perspective, focuses on the focal firm's network structures and positions. The second, the "alter" perspective, concentrates on the network characteristics of a firm's alters. While the early R&D partnership studies largely adopt the ego network approach, the alter perspective has only recently begun to attract scholarly attention [16], [17]. The alter network approach believes that when a firm's R&D partners have superior network structures, they bring additional benefits to focal firms due to the positive externalities of social capital. When a firm's R&D partners occupy structural holes or central positions in a network, the advantageous network structures not only bring benefits to themselves, but also create value for the focal firms. From the focal firms' perspective, collaborating with R&D partners with superior network positions can

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Galunic, et al. [18] conceptualized such externality in social networks as second-order social capital. In contrast to first-order social capital, which refers to the social structures surrounding a network actor, second-order social capital refers to the social structures that surround a network actor's contacts. Although the literature emphasizes the extensive potential benefits of inter-firm networks, researchers have also identified the possibility of negative impacts due to network characteristics and the diffusion process [19]. As a partnership stabilizes, firms will become increasingly familiar with each other's knowledge. In other words, stability can hinder knowledge flows between firms due to a reduced quantity and quality of new information and knowledge. Locking firms into low value networks can also stifle knowledge flows, resulting in negative impacts on a firm's innovation performance. Network researchers have highlighted the need for ongoing network reconfiguration and evolution [20]. As such, it is important to examine the role of relationship duration in relation to second-order social capital and a firm's innovation processes.

We initiated this study to advance understanding of knowledge flows in R&D partnerships and firm innovation. Marrying a social network perspective with a knowledge-based view, we aim to answer the following research question: *If a firm's R&D partners occupy superior network positions, will the second-order social capital increase knowledge spill-in into the focal firm, and improve the firm's innovation performance?* As illustrated above, our motivation for this study stems from two major research gaps in the extant literature. The first is the lack of nuanced understanding of how and when a firm gains knowledge benefits from R&D collaborations for firm innovation. The second gap is the lack of research on the impact of second-order social capital in R&D networks. We address the first research gap by leveraging the knowledge spill-in perspective to study the main effects and the contingency role of relationship duration. We address the second research gap by examining different types of R&D network positions, i.e., structural holes and centrality, and how they influence knowledge spill-in and a firm's innovation performance. To test the hypotheses, we collected a large dataset from Chinese listed companies. Our research findings confirm the positive impact of R&D partners' network positions on knowledge spill-in and focal firms' innovation performance. We also find that relationship duration has an inverted U-shape moderation effect in the relationship between second-order social capital and knowledge spill-in.

In the following sections, we first review the literature and introduce the theoretical foundations. We then explain our hypotheses development. The methodology section describes the sample and data collection process and provides details about the measurements and statistical analysis. We discuss the research findings in the last two sections, focusing on the theoretical and practical implications. We conclude the paper with suggestions for future research.

## II. Theoretical Background

### *A. Knowledge Spill-in in Inter-firm Networks*

Inter-firm networks are considered an important aspect in a firm's innovation process [21]. They often take the form of strategic alliances, R&D partnerships, or research joint ventures; such agreements result in frequent and repeated interactions [22], [23]. According to the resource-based view of the firm, the heterogeneity in a firm's capability and resources are a source of competitive advantage. The exchange of complementary resources in inter-firm networks enables a firm to improve their internal capabilities and advance its innovation performance [24]. The knowledge-based view further suggests that knowledge is a key resource underlying new value creation, which drives a firm's productivity and competitive advantage [25]. The flow of knowledge across organizations increases a firm's access to, and recombination of, diverse knowledge, while simultaneously fostering innovation [26]. Prior research has found that access, acquisition, exchange, and the creation of knowledge are key reasons why firms build networks and/or form strategic alliances [27], [28].

Knowledge acquisition and transfer are often costly process as they involve cross-party compensation for the value of the knowledge exchanged between firms [29]. As a quasi-public good, the reproduction, diffusion, and usage of knowledge cannot be taken for granted [30]. Privately-held knowledge can be considered an asset and thus, creates barriers in respect to inter-firm collaborations. In contrast, while knowledge spillover provides many benefits, these are often at a lower cost as the knowledge flows are often uncompensated or undercompensated [31]. Knowledge spillover happens due to the nature of nonexcludability and nonexhaustibility of knowledge; one party's use of a piece of knowledge neither precludes others from using the same piece of knowledge nor extinguishes the value of that knowledge [32].

Inter-firm knowledge flows, which are often referred to as knowledge spillovers, have been identified as an important antecedent of R&D collaboration [12]. However, the relationship between knowledge spillover and R&D cooperation is complex as knowledge can flow from the focal firm's to partners (outgoing) or flow from partners to the focal firm's (incoming). In their study of R&D cooperation and knowledge spillovers, Cassiman and Veugelers [9] have argued that it is important to differentiate the information flows as the different directions of knowledge spillovers between firms can have varied effects on a firm's innovation management decisions and outcomes. The incoming knowledge flow, which is often referred to as knowledge spill-in or incoming knowledge spillover, enables participating firms to gain extensive benefits from the partnership; thus, it has been found to be positively associated with a firm's propensity to

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engage in R&D collaboration [2]. In contrast, outgoing knowledge flow may reduce a firm's intention to collaborate due to the risk of undesirable information leakage and outflows about a firm's innovation efforts [33]. Many firms attempt to maximize knowledge spill-in and minimize outgoing knowledge spillover in R&D collaborations [34].

Prior research has provided evidence related to the different factors that influence knowledge spill-in, such as a firm's learning orientation, absorptive capability, and the nature and structures of R&D collaborations [35]. In this study, we adopt social network and social capital theory and explore how social capital generated in inter-firm networks influence knowledge spill-in and a firm's innovation performance. The next section introduces the concept of "second-order social capital" that results from location advantages associated with social networks.

### *B. Network Position and Second-Order Social Capital*

Network scholars have found that certain network positions, such as the degree centrality or brokerage across the structural holes between groups, create competitive advantages and provide superior social capital [36], [37]. Individuals or organizations that are located in the brokerage position are more likely to access diverse information, which enhances the possibility of innovation. In contrast, centrally-located actors are often perceived as trustworthy, which facilitates the flow of information with other actors via a short path [1], [12]. Such a process improves efficiency. While a firm's network position and structure influences its innovation performance, second-order social capital also plays a critical role. If a firm is connected with other firms that have superior network positions, it is more likely to benefit from the positive externalities of social capital [38]. As Adler, et al. [39] have noted, "in life, we cannot expect to derive any value from social ties to actors who lack the ability to help us" (p. 26). The magnitude of resources accessible through one's network can be considered a function of the alters' resources [40]. Galunic, et al. [18] have further differentiated between first-order social capital and second-order social capital, conceptualizing first-order social capital as the social structure of the focal actor and second-order social capital as the social structure that surrounds a network actor's contacts. They have argued that second-order social capital has externalities that are independent of the structure of that actor's direct ties, and can spill over the social networks and add value to others' performance. According to Galunic, et al. [38], the positive externality approach to social capital is different from the private benefits perspective (which focuses on an actor's network to his/her private benefits) as it moves towards a more public goods approach. The shift towards the alter perspective focuses on resources, information, and knowledge controlled by alters and views access to them as important explicators of focal actor's outcomes [41]. As Zaheer and Bell [42] have argued, a firm's resources and capabilities not only depend on their own network structure, but also the ones they are linked with; that is, the firm's alters. Thus, it is important to consider the patterns of the firm's ties as well as the resource endowments of their alters to more fully understand the impacts on the consequent performance of the focal firm's.

In line with ongoing discussions on the positive externalities of social capital, we focus on two aspects of R&D partners' network positions: *centrality* and *structural holes*. Network centrality explains the degree to which a firm has quick and independent access to other firms in a network through the fewest possible links [43]. As shown in Fig. 1, if the R&D partner of the focal firm *F* is *P*, then P's degree centrality measures the number of direct connections with other firms. *P* has four direct connections in the network (i.e., *P1*, *P2*, *P3,* and *F*), while *P1* has only two direct connections (*P* and *P2*) in the network, so *P* is in a more central position when compared to *P1*. The high centrality indicates that the R&D partner is at the core of the cooperation network. In contrast, low centrality indicates that the R&D partner is on the edge of the cooperation network. Structural holes focus on the indirect connection [36], [44]. As shown in Fig. 1, since there is no direct connection between *P1* and *P3*, then *P* acts as a "bridge" between *P1* and *P3*. *P* forms a structural hole position, between *P1* and *P3*. In contrast, the structural hole of *P* between *P1* and P2 does not exist because of the direct connection between *P1* and *P2*. Partners occupying the structural hole position can send more non-redundant information to the focal firm [36]. The partners occupying the structural hole position are more likely to access diverse information, which enhances their possibility of innovation [37], [44].

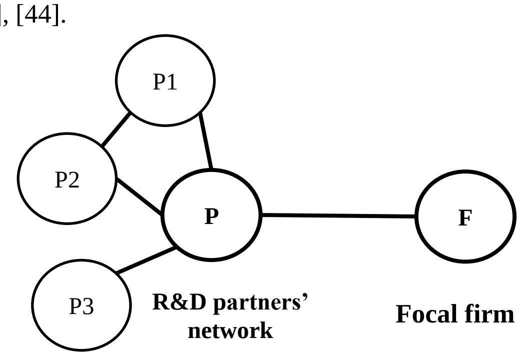


**Fig. 1.** Example of R&D partners' network positions.

Existing research mainly focuses on the impact of the ego network position or the direct impact of the partners' network structures on the focal firm's performance. There is limited research on the underlying mechanism. We investigate this issue and examine the boundary conditions through which partners' network positions influence the focal firm's level of innovation. We discuss our theoretical foundation below.

## II. HYPOTHESES DEVELOMENT

### *A.R&D Partners' Network Position and Knowledge Spill-In*

*R&D partners' network centrality and knowledge spill-in*

Different network positions provide firms with different opportunities to access external information and knowledge. Firms that are centrally located are often in an important and visible spot in the network, a position which enables them to gather a variety of information or control the information flows. Network centrality measures which organizations are key in the flow of information and exchange of knowledge within the network structure [45]. Centrally positioned firms are more likely to receive complete and accurate (less 'filtered') information. If a focal firm partners with centrally located actors, it can gain access to multiple information channels and benefit from the information advantage brought by the partners. R&D partners with high network centrality make it easier to integrate and coordinate with the actions of others, thereby further enhancing their access to rich technologies and knowledge [46]. According to the knowledge-based view of the firm, critical information and knowledge are valuable assets and enhance a firm's competitive advantage. Being connected with centrally located R&D partners increases the firm's chance of knowledge spill-in, which, in turn, will fuel innovative activities by providing valuable information to generate new ideas.

Furthermore, the R&D partners' network centrality reveals their ability to build connections with others and facilitates joint learning. As Zhang and Tang [47] argued, a knowledge element with a high degree of centrality has greater potential to be combined with other knowledge elements. Through inter-firm the interactions, the focal firms can learn from their R&D partners and enhance their dynamic capabilities. Such joint learning saves the focal firm time and energy because they do not need to search for information due to the collaborative advantages gained from the partnership. As a result, the focal firms can spend more time and effort on the development of new ideas and new relationships. They can use these spare resources to seek more business opportunities.

In addition, the R&D partners who are centrally located often have richer social capital and higher network status. In their study of the knowledge spillover effect in corporate financing networks, Uzzi and Gillespie [48] found that competencies and resources can be transferred between network actors and used to enhance the transactions with a third actor. This network transitivity allows focal firms to retrieve strategic resources from their R&D partners and use these resources to gain value from the exchange with an independent third relation. This process enriches the focal firm's social capital and increases the number of channels for knowledge spill-in. Furthermore, alliances are considered an effective means of obtaining status support in an institutional environment [49]. R&D partners who are centrally located often have high network status. This characteristic provides additional benefits to firms that are connected with them, as the high network status of R&D partners may bring the firm reputation advantages. They can also gain from well-connected partners by applying partners' knowledge or practices to respond to emerging market trends and ultimately increase their profitability [46]. Collaborating with central R&D partners often brings reputational benefits to the focal firm, which result in long-term effects such as improving the focal firm's trustworthiness and attracting other R&D partners for innovative projects.

In sum, we argue that R&D partners' network centrality should contribute to the knowledge spill-in to the focal firm. Thus, we propose the following hypothesis:

***Hypothesis 1:*** *R&D partners' network centrality is positively associated with the degree of knowledge spill-in to the focal firm.*

*R&D partners' structural holes and knowledge spill-in*

In organizational research, structural holes have been extensively studied as a network position that is relevant to a firm's innovation performance [50]. Due to the knowledge spillover and spill-in effects in structural holes, firms are likely to benefit from the informational benefits of brokerage [51]. However, prior research has reported mixed results on the impact of structural holes on innovativeness. For example, Reagans and Zuckerman [52] found that structural holes – which were measured using network heterogeneity – had a significantly positive impact on team productivity, and that teams with heterogeneous networks were more productive than teams with homogeneous networks. In contrast, Obstfeld [53] has argued that while structural holes lead to good ideas, they may not have a direct impact on innovation.

In this study, we argue that the degree to which R&D partners bridge structural holes should have a positive impact on the focal firm's innovativeness due to knowledge spill-in. If R&D partners are located at the brokerage position, they have non-redundant connections with heterogeneous network actors. This finding provides a vision of options otherwise hidden [36], [44], and means that the connected actors are exposed to different perspectives and ideas. By cooperating with firms occupying the brokerage position of structural holes, the focal firms can benefit from knowledge sharing and the cross-fertilization of ideas. In his classic article, Granovetter [54] argued that while strong ties (direct) restrict information flows from outside sources, weak tie relations (indirect and informal) provide greater access to new information and opportunities. In the study of indirect networks, i.e., an actor's indirect ties in a network, Hirst, et al. [55] proposed the concept of reach efficiency, which refers to the extent to which the indirect network provides an actor access to non-redundant information. They argued that the reach efficiency of a network has a positive impact on individual creativity because creativity benefits from exposure to diverse new ideas and perspectives. If an indirect network has higher reach efficiency, actors in the network can gain access to more diverse information while minimizing redundant ideas. Following this logic, firms with R&D partners who bridge structural holes in a network have better reach efficiency to diverse information and unique perspectives from different sources. This feature expose firms to previously unrelated knowledge and increases the chances of new ways of doing things.

Furthermore, the R&D partners who bridge structural holes play critical roles in information diffusion. They can act as gatekeepers and influence how information is distributed across communities. For example, Lou and Tang

[56] studied the brokers in online social networks, which they referred to as structural hole spanners. Using data mining methods, they found that "the top 1% of structural hole spanners control almost 80% of the information between different communities" (p. 839). As the information hub, brokerage across structural holes greatly influence the quantity and quality of information which passes through the networks. New knowledge elements from partners with rich structural holes suggest that many knowledge elements in the egocentric knowledge domain of these new knowledge elements have not been combined and thus provide rich combinatorial opportunities for focal organizations to investigate in the future [47]. In contrast, new knowledge elements from partners with few structural holes suggest that the knowledge elements of their egocentric knowledge domain have been extensively combined, thus resulting in fewer untapped combinatorial opportunities [57]. Such firms are more likely to become opinion leaders and have a greater impact upon other actors in the networks. Firms should carefully consider whom they partner with as this will determine the nature and volume of the knowledge spilled into the focal firm. Thus, we propose the following hypothesis:

***Hypothesis 2:*** *R&D partners' structural holes are positively associated with the degree of knowledge spill-in to the focal firm.*

### *B. Knowledge Spill-In and Focal Firm's Innovation Performance*

Network scholars have argued that innovation, whether it is undertaken internally or externally, is a complex process that requires the flow of knowledge between firms [26]. They contend that successful innovation depends on access to, and the integration of, new knowledge in the innovation process. Furthermore, they have claimed that it is important for firms to innovate effectively through interactions with external actors instead of in isolation [58]. According to Ahuja [59], there are two major benefits in inter-organizational collaborations: resource sharing and knowledge sharing. Knowledge, which can also be considered a strategic resource, brings information advantages to the collaborative partners, such as helping firms reduce their search costs [60] and gaining access to each other's knowledge pool [61]. Through inter-organizational networks, firms enrich their respective knowledge stocks [59] and enjoy the advantage of specialization. The accumulation of external knowledge can also enhance an organization's ability to generate new ideas, and their ability to convert this knowledge into further innovations [62].

From a focal firm's perspective, knowledge spill-in can bring the most benefits and contribute to the firm's existing knowledge stock, ultimately enhancing their innovation capabilities [63]. The focal firm can directly access other firms' capabilities through inter-organizational networks [64] or acquire new capabilities through organizational learning [60]. Prior research has shown that there is a positive relationship between knowledge spill-in and a firm's innovation performance. For example, Cassiman, et al. [65] found firms that have access to external knowledge are more likely to engage in basic research than applied research, which increases the likelihood of radical innovation.

Furthermore, firm innovation often relies on the recombination of diverse and complementary knowledge. For example, Kogut and Zander [66] introduced the concept of a combinative capability to synthesize and apply current and acquired knowledge, which has an important impact on firm innovation. When there is a high level of knowledge spill-in from R&D partners, the focal firms can promptly retrieve useful information or select the knowledge they need from a large knowledge pool for the development of innovation. Knowledge spill-in allows firms to gather complementary knowledge from other firms and get involved in collaborative innovation activities. Such inter-firm knowledge transfer can improve the focal firm's dynamic capabilities by supporting the focused exploitation of existing capabilities within the firm [64]. Through the combination of existing and new knowledge, a focal firm can gain new insights and generate innovative ideas [63].

In sum, knowledge spill-in enlarges a focal firm's knowledge base by accessing R&D partners' knowledge beyond what is locally available. Furthermore, it creates more opportunities for the focal firm to acquire, recombine, and reorganize knowledge, and increases a firm's dynamic capabilities through organizational learning. Thus, we argue that knowledge spill-in should have a positive impact on a firm's ability to generate innovations.

***Hypothesis 3:*** *Knowledge spill-in is positively associated with the focal firm's innovation performance.*

### *C. Moderating Effect of Relationship Duration*

Although inter-firm networks bring potential benefits to firms, it is also important to highlight the possibility of negative impacts [21]. For example, long-term partnership may result in unproductive networks with stagnated knowledge flows [67], due to the dynamic nature and changeability of networks. Prior research has suggested that networks require diversity [60]. Firms need to continuously reconfigure their networks by updating and changing contacts [68]. As such, relationship duration is an important factor that can potentially moderate the knowledge benefits in inter-firm networks. The duration of a relationship is the length of time that a relationship between exchange partners has existed [69], [70]. Relationship duration refers to the stability and closeness of the relationship between partners in R&D networks [48]. In this study, we argue that while a relatively short relationship (duration) facilitates knowledge spill-in to the focal firm, an excessively long relationship (duration) hinders knowledge spill-in. Relationship duration should play an inverted U-shaped moderating role between R&D partners' network position (network centrality and structural holes) and knowledge spill-in. The reasons are explained below.

In networks where R&D partners are centrally located, an appropriate length of relationship duration between the focal firm and R&D partners can foster strong ties, leading to frequent and high-quality knowledge flows. Collaborative R&D activities often require a high level of trust between partnering firms due to the potential risk of knowledge leakage [71]. Firms that partner with each other on innovative projects need to develop an understanding as to which knowledge can be shared or which should remain within the firm [72]. An appropriate length of relationship duration often involves building trust and understanding, which is crucial for effective knowledge transfer. If trust exists, the knowledge shared will not be misappropriated or misused; a firm's willingness to share valuable information is dependent upon trust. Relationship duration can facilitate cooperation and knowledge sharing through the building of trust. Likewise, an established relationship reduces negotiation and communication costs related to knowledge transfer. Moreover, the right duration facilitates knowledge flow between firms. Due to the close relationships, knowledge transfers may become spontaneous behaviors beyond formal institutional activities. Such behavior will greatly decrease the cost of supervision and negotiation in the implementation of these activities.

However, as Uzzi [73] has noted, overly prolonged relationships may lead to a situation where firms become over-embedded in their existing networks. This over-embeddedness can result in a focus on homogenous knowledge, limiting exposure to diverse and novel ideas essential for breakthrough innovations. Specifically, there is a risk of over-embeddedness, leading to resistance to new ideas, and innovation inertia. An excessively long relationship (duration) may lead to homogenization of the knowledge that the focal firm acquires from partners. The knowledge stock of a single partner is limited [74], and the knowledge that a focal firm can acquire from a specific partner is also limited. When the focal firm spends too much time and effort on maintaining relationships with specific partners, it may result in homogeneous knowledge and discourage the firm from acquiring heterogeneous knowledge from other firms. Building upon these arguments, we propose the following hypothesis:

***Hypothesis 4:*** *The relationship duration between R&D partners and the focal firm plays an inverted U-shaped moderating role between R&D partners' network centrality and knowledge spill-in.*

In the context of structural holes, as conceptualized by Burt [36], an appropriate relationship duration can be advantageous as it allows firms to bridge diverse information sources, bringing in fresh ideas and novel information. This view aligns with Burt's argument that bridging structural holes provides access to a variety of information, fostering innovation. Specifically, knowledge diffusion is an accumulative process and the development of innovation is iterative. Collaborative R&D activities often take time. Much effort is expended building common ground for partnering firms to exchange ideas. Each firm has its background, value system, perspective, and expertise. Moreover, the establishment of knowledge-sharing routines evolves over time [75]. In this case, the quantity and quality of knowledge spilled into the focal firms are conditioned by the relationship duration between partnering firms.

Granovetter's [54] concept of the strength of weak ties, however, suggests that overly strong ties, which may result from an excessively long relationship (duration), might limit the diversity of information accessed, as these relationships tend to circulate redundant information. An excessively long relationship (duration) may lead firms to rely more on knowledge from a "small world network", thus excluding or neglecting the acquisition of diverse and heterogeneous knowledge from outside [71]. For example, Brian and Jarrett [76] found a parabolic relationship between a small world and the performance of the actors within it, such that when performance increases to a threshold, the positive effects reverse. Chen and Guan [71] have argued that the relationship between small-world structure and innovation performance is parabolic, and that while small-world structure benefits innovation, it is limited to a special range, after which the effects reversed. The shorter path length always correlates with increased innovation output. As a result, the "small world network", formed by the long relationship (duration) of the focal firm and its partners, presents a barrier to innovation due to the exclusion of heterogeneous knowledge from the outside world [77]. In addition, an excessively long relationship (duration) may mean that the firm falls into past innovation patterns and has a path-dependency orientation [78]. A stronger path dependence can also lead firms to focus too much on established knowledge and information and even fall into the "competence trap" [79], thereby weakening knowledge spill-in from the structural hole in the R&D partner's network. Therefore, we propose the following hypothesis:

***Hypothesis 5:*** *The relationship duration between R&D partners and the focal firm plays an inverted U-shaped moderating role between R&D partners' structural holes and knowledge spill-in.*

Fig. 2 summarizes our research framework, which illustrates the key factors that influence focal firm innovation performance in R&D partnerships.

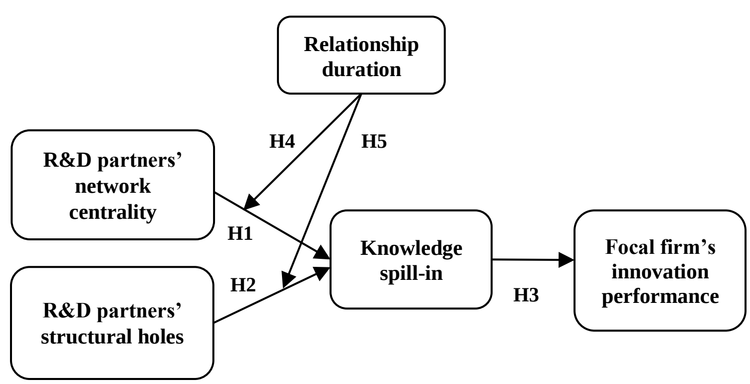


**Fig. 2.** Research framework

## III. Methodology

### *A. Sampling and Data Collection*

We selected a sample of publicly listed Chinese firms on the Shanghai and Shenzhen stock exchanges to test our hypotheses. Over the past two decades, China has developed rapidly in technological innovation. In 2006, Chinese government deployed an 'indigenous innovation' policy to promote domestic technology development. Since then, China's innovation activities, reflected in patent applications, have grown rapidly. According to the World Intellectual Property Organization, China has ranked the first in international patent applications for three consecutive years: 2019, 2020, and 2021. The abundance of patent applications provides us with rich data to examine firms' innovation activities. Furthermore, the modern corporate governance system is a new development in Chinese listed firms [80]. Knowledge and information not only flow through formal connections but also through informal networks. As an unspoken rule in relationship building, firms often have reciprocal obligations to benefit each other in these contexts. Using China's data can enrich our understanding about other countries that share similarities.

The data were collected from multiple sources. We first retrieved Chinese listed firms' *patent data* from China's State Intellectual Property Office (SIPO). We obtained a variety of information including the patent number, the patent name, the firm (assignee) name, the inventors' names, the date of application, and the patent category, among other relevant details. This data helped us identify the R&D partners of focal firms, and also served as the basis for the measures of R&D partners' network positions (i.e., degree centrality and structural holes). We then collected the *patent citation data* from the Chinese Research Data Services Platform (CNRDS). CNRDS draws on the Wharton Research Data Service (WRDS) and other international data platforms to build China's research data resources. This high-quality comprehensive data platform is used for economic, financial, and business research in China. The data from CNRDS includes mutual citations of patents among firms, which allows us to measure the knowledge spill-in effect as patent citations are commonly used as indicators of knowledge flows between firms [5], [6]. In line with the extant literature [81], we collected the firms' *background information* to use as control variables, including firm size, age, general performance, growth performance from the China Stock Market & Accounting Research Database (CSMAR).

Although we obtained Chinese listed firm data for the period between 2000 and 2020, we only used data from between 2007 and 2019 in final analysis for the following reasons. First, Chinese listed companies have only been required to disclose R&D inputs since 2007. We thus chose to begin our study from 2007 to ensure a sufficiently large sample and ensure we had complete data to examine Chinese firms' technological innovation activities. Second, unlike Western countries, the Chinese government closed down some cities during the initial COVID-19 outbreak. For example, Wuhan city was closed from the 23rd of January 2020 to the 8th of April 2020. City buses, subways, ferries and long-distance passenger transport in Wuhan were all suspended, and the airport and railway stations were temporarily closed for departures from Wuhan. Other cities such as Chongqing (from the 22nd of January 2020 to the 8th of February 2020), Shijiazhuang (from the 6th of January 2021 to the 29th of January 2020), Changchun (from the 11th of March 2022 to the 28th of April 2022) and Shanghai (from the 28th of March 2022 to the 1st of June 2022) also encountered similar situations. The closure of these cities had a critical impact on the mobility of the firms' inventors, cooperation between firms, and the innovation process, which, to a certain extent, hindered individual and firm innovation. More importantly, as relevant studies have noted, that the COVID-19 pandemic has had a significant impact on firms' business decisions, cooperation paths, and innovation models [82]-[85]. For example, Ding, et al. [84] found that the lockdown of the Hubei province negatively affected firms' decisions, and firms with the province of Hubei exposures earned significantly lower returns. Jin, et al. [85] found that COVID-19 significantly and negatively affected the quality and quantity of innovation in China, and that COVID-19 had a greater negative effect on the innovation quality of state-owned enterprises (SOEs). Therefore, taking into account of the impact of COVID-19 in China, we chose to exclude the data from 2020.

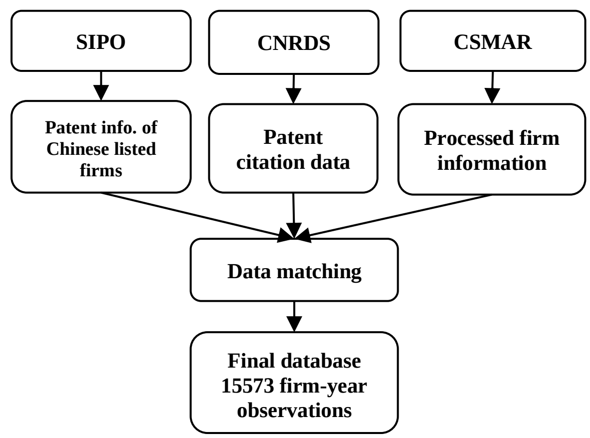


Fig. 3. Data processing and matching

We matched data collected from different sources based on the firm's name, stock code, and the year the firm was established. Referring to existing studies, we excluded ST and PT companies and ones that were missing financial data. When a company's status is ST or PT, it means that the company is in a state of abnormal operation, including long-term financial abnormalities and the suspension of stock circulation. In this case, the financial data and operational performance of the company are not representative. Therefore, we have excluded this part of the sample. To avoid the influence of outliers, all continuous variables were winsorized at the upper and lower 1% levels [81]. We illustrate our data retrieving and matching process in Fig. 3. The final sample used for analysis consisted of 15,573 firm-year observations from 2,015 Chinese listed firms between the years 2007 and 2019. In *Table II*, we report the distribution of each year and each two-digit industry.

### B. Measures

***Focal firm's innovation performance*** *(Inno_Pfm)*. In line with previous research, we measured innovation performance using the total number of patent applications each firm made in a given year [86]. To avoid the problem of excessive dispersion of the number of firm patents, we took the logarithm of the total number of patents plus one.

***R&D partners' network centrality*** *(Partner_C)*. Following Sytch and Tatarynowicz [87], we used degree centrality to measure the R&D partners' network centrality. Specifically, we measured it noting the total number of ties held by the partners in year *t*, as shown in Eq. (1)

$$Partner\_C_{it} = \frac{\sum_j x_{jit}}{(g-1)} \quad (1)$$

Where *i*, *j* refer to different firms, and $X_{ijt}$ indicates that firm *i* and *j* have an R&D cooperative relationship in year *t*; *g* represents the number of firms that participated in the establishment of an R&D network. When a focal firm has multiple R&D partners in the given year, R&D partners' network centrality is the mean of the degree centrality of all partners.

***R&D partners' network structural holes*** *(Partner_SH)*. Following Zaheer and Bell [42], we chose a variable that measures the impact of structural holes while taking into account the decline in tie strength of more distant ties. We measured the structural holes of each partner using the following formulas:

$$Partner\_SH_{i,t}=2\text{-}C_{it} \quad (2)$$

$$C_{i,t} = \sum_{j=1}^{n} C_{ijt}, i \neq j \quad (3)$$

$$C_{ijt} = (P_{ijt} + \sum_q p_{iqt}\, p_{jqt})^2, q \neq i \neq j \quad (4)$$

$C_{it}$ in Eq. (2) is a network constraint on partner *I*; it is calculated based on $C_{ij}$, a measure of *i*'s dependence on contact with *j in* Eq. (3). $C_{ij}$ is calculated as Eq. (4), where *q* refers to a node besides *i* and *j*. $P_{ij}$ is the proportion of *i*'s direct connections with *j*. $\sum_q p_{iqt}\ p_{jqt}$ is the proportion of i's indirect connections with j through the path of all connecting with q. Similarly, when a focal firm has multiple R&D partners in year *t*, the R&D partners' structural holes are the mean of the structural holes of all partners.

***Knowledge spill-in (****Knowlge_spill-in****)***. Following Kim and Steensma [6] and Tzabbar, et al. [5], we used patent citations to measure knowledge spill-in from the R&D partners to the focal firms. In particular, taking into account the existence of patent citation without collaboration, we removed the number of patents cited as non-cooperative. Specifically, we used the following metrics to measure knowledge spill-in: the first metric, *Knowlg_clear*, refers to the number of times that the cooperative patents of the focal firm cited the partner's patent in the year of observation. The second metric, *Knowlg_direct*, refers to the number of patents that the focal firms directly cite from their partners' patents in the year of observation. The third metric, *Knowlg_total*, refers to the number of total patents that the focal firms cite from their partners in the year of observation (including direct cites from partners and indirect cites from other firms).

***Relationship duration*** *(Duration)*. Following Isaksson, et al. [75], we used the number of years that a focal firm and partner are linked, as a measure of the relationship duration. When an enterprise had multiple R&D partners in a focal year, we calculated relationship duration using the mean of the total years of all partners.

***Control variables***. Following Liu, et al.'s [81] suggestion, we included several control variables: R&D expenditure (*RD*), firm *Size* (logarithm of the firm's total sales), *Age* (the number of years since the firm was founded), *ROA* (firm performance), *SOE* (coded as 1 if the firm is a state-owned enterprise, 0 otherwise), *Lev* (the level of firm leverage), *Growth* (firm's highly growing index), *TobinQ* (the future investment opportunities). In addition, considering that the characteristics of the partners may also have an impact on the focal firm innovation, we also included controls for the R&D partner's characteristics: *Partner_RD*, *Partner_Lev*, *Partner_ROA*, *Partner_Growth*, *Partne_Size*, *Partne_SOE*, *Partne_Age*. In addition, to control for any unmeasured period-specific and industry-specific effects, we included dummy variables: *Year* and *Industry*. We provide a list of definitions for these variables in *Table I*.

TABLE I
THE DEFINITIONS AND MEASURES OF VARIABLES

| Variable | Notation | Definition |
|---|---|---|
| Firm's innovation performance | *Inno_Pfm* | Logarithm of the total number of each firm's successful patent applications, plus one. |
| Partners' network centrality | *Partner_C* | We use degree centrality to measure R&D partners' network centrality. |
| Partners' network structure holes | *Partner_SH* | We use the opposite of the total network constraint to measure R&D partners' network structural holes. |
| Knowledge spill-in | *Knowlg_clear* | Logarithm of the number of times the cooperative patents of focal firm cited the partner's patent on the year of observation. |
| | *Knowlg_direct* | Logarithm of the number of times the focal firm cited the partner's patent on the year of observation. |
| | *Knowlg_total* | Logarithm of the number of times the focal firm cited other firms' patent on the year of observation. |
| Relationship duration | *Duration* | The number of years that a focal firm and partner are linked in our data set as a measure of the relationship duration. |
| Focal firm control | *RD* | Logarithm of total R&D expenditure of focal firm. |
| | *Lev* | The ratio of the total debts to total assets at every year's end. |
| | *ROA* | The firm's profit divided by total assets. |
| | *Growth* | The ratio of the operating income changes to the operating income in the previous period at every year's end. |
| | *TobinQ* | Enterprise market value/capital replacement cost at the end of year t. |
| | *Size* | Logarithm of the firm's total assets. |
| | *SOE* | Coded as 1 if the firm is a state-owned enterprise, 0 otherwise. |
| | *Age* | The number of years since the firm was listed. |
| Partners' control | *Partner_RD* | The ratio of the total debts to partner's total assets. |
| | *Partner_Lev* | The ratio of the total debts to partner's total assets. |
| | *Partner_ROA* | The firm's profit divided by partner's total assets. |
| | *Partner_Growth* | The ratio of the operating income changes to the operating income in the previous period of partners. |
| | *Partner_Size* | Logarithm of the firm's total assets of partners. |
| | *Partner_SOE* | Coded as 1 if the firm is a state-owned enterprise, 0 otherwise. |
| | *Partner_age* | The number of years since the firm was listed. |

### C. Research Model

To test the research hypothesis, we established the following research models:

$$Knowlg_{i,t} = \alpha_0 + \alpha_1 Partner_{i,t-1} + \alpha_2 Control_{i,t-1} + Year_{t-1} + Industry_i + \varepsilon \quad (5)$$

$$Patent_{i,t} = \beta_0 + \beta_1 Knowlg_{i,t-1} + \beta_2 Control_{i,t-1} + Year_{t-1} + Industry_i + \varepsilon \quad (6)$$

$$Knowlg_{i,t} = \gamma_0 + \gamma_1 Partner_{i,t-1} * Duration_{i,t-1} + \gamma_2 Partner_{i,t-1} * Duration_{i,t-1}^2 + \gamma_3 Duration_{i,t-1} + \gamma_4 Duration_{i,t-1}^2 + \gamma_5 Partner_{i,t-1} + \gamma_6 Control_{i,t-1} + Year_{t-1} + Industry_{i,t-1} + \varepsilon \quad (7)$$

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$$Patent_{i,t} = \delta_0 + \delta_1 Knowlg_{i,t-1} * Duration_{i,t-1} + \delta_2 Knowlg_{i,t-1} * Duration^2_{i,t-1} + \delta_3 Duration_{i,t-1} + \delta_4 Duration^2_{i,t-1} + \delta_5 Knowlg_{i,t-1} + \delta_6 Control_{i,t-1} + Year_{t-1} + Industry_{i,t-1} + \varepsilon \quad (8)$$

Equation (5) was used to test the impact of the partner's network position (i.e., *Partner_C* & *Partner_SH*) on knowledge spill-in (i.e., Hypothesis 1 and 2); Equation (6) was used to test the impact of knowledge spill-in on firm innovation (i.e., Hypothesis 3); Equation (7) was used to test the inverted U-shaped moderating effect of duration between the partner network position and knowledge spill-in (i.e., Hypotheses 4 and 5); Equation (8) was used to test the moderating effect of duration between knowledge spill-in and the focal firm's innovation (i.e., Hypothesis 6). *Patent* is the dependent variable, using the number of patent applications of the focal firm; *Partner* is the partner network position, including the partner network degree centrality (*Partner_C*) and structural hole index (*Partner_SH*); *Knowlg* is the index of knowledge spill-in; *Duration* is the relationship duration. *Control* represents a series of control variables, *Year* and *Industry* are year and industry fixed effects, respectively. Considering the lag of firm innovation, and following Chu, et al. [86], the dependent variable was delayed in one phase.

## V. DATA ANALYSIS AND RESULTS

### A. Network Structures and Descriptive Statistics

Fig. 4 and Fig. 5 present the R&D networks we constructed from the data. The direction of the arrow indicates the direction of knowledge flow. The thickness of the line indicates the number of citations (i.e., the degree of knowledge flow). The closed circle on the node indicates that the firm cites its patents. The results indicate that the majority of firms established collaborations with other firms, and were embedded in large R&D networks. However, many of the firms tended to cite more of their own patents than other firms' patents. In some extreme cases, firms only cited themselves, e.g., the firm with stock code 600535, which indicates the development of innovation by themselves. According to Greve and Seidel [88], the high-level of self-citing ratios indicates a strong path-dependent orientation, which may impede a firm's innovation performance. Initial examination of the network structure showed that our data had a wide range of variations in terms of the firms' network positions, which provided adequate information for us to perform the hypotheses testing.

*Table II* presents the distribution of each year and each industry. Panel A reports the observations and their proportions for each year, showing an increasing trend overall. Panel B reports the observations and their proportions for each two-digit industry. Among them, the manufacturing industry has the largest observations and proportion; this finding was not unexpected as most listed Chinese enterprises engage in manufacturing.

*Table III* and *Table IV* present the descriptive statistics and correlation matrix for all of the variable. The average number of patents applied by the firms was 1.473 (*S.D.* = 1.711) with a maximum number of 6.805, findings which are consistent with those of previous studies. The mean value of *Knowlg_direct* was 0.414 (*S.D.* =0.864), the mean value of *Knowlg_total* is 0.568 (*S.D.* = 1.050), and the mean value of *Knowlg_clear* was 0.388 (*S.D.* =0.867).

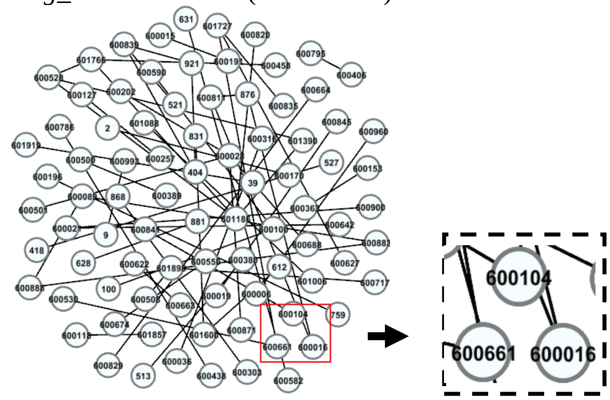

Fig. 4. Example of the R&D network (partial)

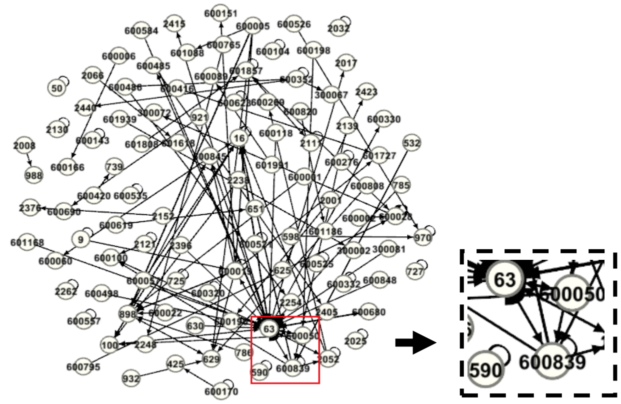

Fig. 5. Example of directions of knowledge flow

TABLE II
YEAR AND INDUSTRY DISTRIBUTION

**Panel A: Year Distribution**

| Year | Observations | Percent (%) |
|---|---|---|
| 2007 | 611 | 3.923 |
| 2008 | 783 | 5.028 |
| 2009 | 792 | 5.086 |
| 2010 | 849 | 5.452 |
| 2011 | 865 | 5.554 |
| 2012 | 1255 | 8.059 |
| 2013 | 1329 | 8.534 |
| 2014 | 1409 | 9.048 |
| 2015 | 1482 | 9.516 |
| 2016 | 1513 | 9.716 |
| 2017 | 1548 | 9.940 |
| 2018 | 1540 | 9.889 |
| 2019 | 1597 | 10.255 |
| Total | 15573 | 100 |

**Panel B: Industry Distribution**

| Industry | Observations | Percent (%) |
|---|---|---|
| Agriculture, forestry, and fishing | 329 | 2.113 |
| Mining and quarrying | 424 | 2.723 |
| Manufacturing | 8,851 | 56.836 |
| Electricity, heat, gas, and water production and supply | 342 | 2.196 |
| Construction | 435 | 2.793 |
| Wholesale and retail trade | 403 | 2.588 |
| Transportation and storage | 348 | 2.235 |
| Accommodation and food service activities | 207 | 1.329 |
| Information and communication | 1092 | 7.012 |
| Real estate activities | 485 | 3.114 |
| Renting and commercial services | 402 | 2.581 |
| Professional, scientific, and technical activities | 389 | 2.498 |

| | | |
|---|---|---|
| Water, environment, and public facilities management | 203 | 1.304 |
| Residential services, repairs, and other services | 210 | 1.348 |
| Education | 306 | 1.965 |
| Health and social work activities | 308 | 1.978 |
| Arts, entertainment, and recreation | 574 | 3.686 |
| Others | 265 | 1.702 |
| Total | 15573 | 100 |

Moreover, as shown in *Table IV*, the correlation coefficients between the independent variables were all less than 0.5, and the average VIF for all variables was 2.34, with the largest VIF being 3.5, a figure below the recommended ceiling of 10. This result suggests that multicollinearity is not a concern in this study.

TABLE III
DESCRIPTIVE STATISTICS

| *VARIABLES* | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| *Inno_Pfm* | 15573 | 1.473 | 1.711 | 0.000 | 6.805 |
| *Knowlg_total* | 15573 | 0.568 | 1.050 | 0.000 | 8.543 |
| *Knowlg_direct* | 15573 | 0.414 | 0.864 | 0.000 | 7.588 |
| *Knowlg_clear* | 15573 | 0.388 | 0.867 | 0.000 | 8.292 |
| *Partner_C* | 15573 | 0.001 | 0.012 | 0.000 | 0.333 |
| *Partner_SH* | 15573 | 0.025 | 0.154 | 0.000 | 1.125 |
| *Duration* | 15573 | 2.826 | 3.324 | 0.000 | 45.000 |
| *RD* | 15573 | 17.228 | 1.852 | 6.908 | 23.683 |
| *Lev* | 15573 | 0.456 | 0.207 | 0.059 | 0.950 |
| *ROA* | 15573 | 0.037 | 0.055 | -0.199 | 0.196 |
| *Growth* | 15573 | 0.200 | 0.418 | -0.511 | 2.653 |
| *TobinQ* | 15573 | 2.015 | 1.745 | 0.199 | 9.740 |
| *Size* | 15573 | 22.035 | 1.303 | 19.570 | 26.069 |
| *SOE* | 15573 | 0.490 | 0.500 | 0.000 | 1.000 |
| *Age* | 15573 | 9.214 | 5.985 | 0.000 | 23.000 |
| *Partner_RD* | 15573 | 17.219 | 1.908 | 6.908 | 23.770 |
| *Partner_Lev* | 15573 | 0.456 | 0.213 | 0.059 | 1.211 |
| *Partner_ROA* | 15573 | 0.039 | 0.056 | -0.341 | 0.202 |
| *Partner_Growth* | 15573 | 0.196 | 0.417 | -0.680 | 3.601 |
| *Partner_Size* | 15573 | 22.011 | 1.440 | 18.868 | 26.379 |
| *Partner_SOE* | 15573 | 0.480 | 0.500 | 0.000 | 1.000 |
| *Partner_age* | 15573 | 8.238 | 5.962 | 0.000 | 26.000 |

### *B. Hypotheses Testing*

*R&D partners' network position and knowledge spill-in*

*Table V* presents the results of the impact of partners' R&D network positions on knowledge spill-in and focal firm innovation performance.[1] As mentioned above, we lagged the main dependent variable *Inno_Pfm* by one year to avoid simultaneity bias and to allow for a time delay in potential patent applications. Columns (1)–(3) report the impact of R&D partners' network centrality and structural holes on knowledge spill-in, and column (4) reports the impact of R&D partners' network centrality and structural holes on focal firm innovation. Specifically, Columns (1)-(3) in *Table V* report the impact of R&D partners' network centrality on knowledge spill-in using different measures. The coefficients of R&D partners' network centrality were 2.978, 1.925 and 2.940, which are significant at 1%, 5% and 1% levels, respectively. These results indicate that the R&D partners' network centrality has a significant positive effect on the knowledge spill-in. In short, *Hypothesis 1 is supported*. Similarly, Columns (1)–(3) in *Table V* also report the impact of R&D partners' network structural holes on knowledge spill-in using different measures. The coefficients of R&D partners' structural holes were 0.114, 0.095 and 0.121, which were significant at 10%, 5% and 5% levels, respectively. These results indicate that the R&D partners' network structural holes have a significant positive effect on the knowledge spill-in, *providing support for Hypothesis 2*.

TABLE V
REGRESSION RESULTS OF R&D PARTNER NETWORK POSITIONS ON KNOWLEDGE SPILL-IN AND FIRM INNOVATION PERFORMANCE

| *VARIABLES* | (1) *Knowlg_total* | (2) *Knowlg_direct* | (3) *Knowlg_clear* | (4) *Inno_Pfm* |
|---|---|---|---|---|
| *Partner_C* | 2.978*** | 1.925** | 2.940*** | 3.467*** |
| | (0.979) | (0.807) | (0.987) | (1.122) |
| *Partner_SH* | 0.114* | 0.095** | 0.121** | 0.617*** |
| | (0.062) | (0.043) | (0.053) | (0.093) |
| *RD* | 0.157*** | 0.122*** | 0.124*** | 0.312*** |
| | (0.009) | (0.008) | (0.007) | (0.012) |
| *Lev* | 0.052 | 0.069 | -0.001 | 0.186* |
| | (0.077) | (0.067) | (0.065) | (0.102) |
| *ROA* | -0.075 | -0.191 | -0.000 | 0.763*** |
| | (0.167) | (0.142) | (0.134) | (0.260) |
| *Growth* | -0.022 | 0.000 | -0.059*** | -0.040 |
| | (0.018) | (0.016) | (0.013) | (0.028) |
| *TobinQ* | 0.021*** | 0.020*** | 0.021*** | -0.018** |
| | (0.005) | (0.005) | (0.004) | (0.008) |
| *Size* | 0.211*** | 0.181*** | 0.159*** | 0.289*** |
| | (0.016) | (0.014) | (0.013) | (0.019) |
| *SOE* | 0.161*** | 0.117*** | 0.156*** | 0.161*** |
| | (0.036) | (0.032) | (0.030) | (0.048) |
| *Age* | -0.011** | -0.011*** | -0.009** | -0.029*** |
| | (0.005) | (0.004) | (0.004) | (0.005) |
| *Partner_RD* | 0.017** | 0.015** | 0.006 | 0.044*** |
| | (0.008) | (0.007) | (0.007) | (0.011) |
| *Partner_Lev* | -0.065 | -0.041 | -0.060 | -0.082 |
| | (0.075) | (0.065) | (0.063) | (0.100) |
| *Partner_ROA* | -0.271* | -0.433*** | -0.193 | 0.696*** |
| | (0.160) | (0.137) | (0.131) | (0.255) |
| *Partner_Growth* | -0.007 | 0.004 | -0.016 | 0.009 |
| | (0.019) | (0.017) | (0.016) | (0.028) |
| *Partner_Size* | 0.018 | 0.018 | 0.018 | -0.006 |
| | (0.014) | (0.012) | (0.011) | (0.016) |
| *Partner_SOE* | -0.021 | -0.006 | -0.060** | -0.114** |
| | (0.036) | (0.032) | (0.031) | (0.047) |
| *Partner_age* | 0.005 | 0.006 | 0.006 | 0.018*** |
| | (0.005) | (0.004) | (0.004) | (0.005) |
| *Year* | Yes | Yes | Yes | Yes |
| *Industry* | Yes | Yes | Yes | Yes |
| *Observations* | 15573 | 15,573 | 15,573 | 15,573 |
| *Adj_$R^2$* | 0.350 | 0.318 | 0.270 | 0.419 |

Note: Robust standard errors in parentheses. *** p<.01, ** p<.05, * p<.10.

*Knowledge spill-in and focal firm's innovation performance*

*Table VI* presents the regression results on the impact of knowledge spill-in on focal firm innovation performance. The coefficients of knowledge spill-in, using different measures, as outlined in Columns (1) - (3) were 0.592, 0.633 and 0.584. These figures were all significant, at the 1% level, indicating that the knowledge spill-in effect has a significant positive effect on the focal firm's innovation performance. Therefore, *Hypothesis 3 is supported*.

Furthermore, we tested the mediation effect of the knowledge spill-in between the R&D partners' network position and focal firm innovation. We used the stepwise

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TABLE IV
CORRELATION MATRIX

| ***VARIABLES*** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Inno_Pfm* | 1 | | | | | | | | | | | | | | | |
| *Knowlg_total* | 0.560*** | 1 | | | | | | | | | | | | | | |
| *Knowlg_direct* | 0.528*** | 0.640*** | 1 | | | | | | | | | | | | | |
| *Knowlg_clear* | 0.500*** | 0.607*** | 0.663*** | 1 | | | | | | | | | | | | |
| *Partner_C* | 0.055*** | 0.041*** | 0.037*** | 0.047*** | 1 | | | | | | | | | | | |
| *Partner_SH* | 0.048*** | 0.01 | 0.014* | 0.018** | 0.616*** | 1 | | | | | | | | | | |
| *Duration* | 0.055*** | 0.006 | 0.007 | 0.011 | 0.285*** | 0.675*** | 1 | | | | | | | | | |
| *RD* | 0.369*** | 0.407*** | 0.395*** | 0.376*** | 0.024*** | 0.003 | 0.019** | 1 | | | | | | | | |
| *Lev* | 0.044*** | 0.067*** | 0.090*** | 0.065*** | 0.022*** | 0.057*** | 0.041*** | 0.017** | 1 | | | | | | | |
| *ROA* | 0.089*** | 0.044*** | 0.029*** | 0.046*** | 0.017** | 0.018** | 0.013* | 0.158*** | -0.396*** | 1 | | | | | | |
| *Growth* | -0.002 | -0.024*** | -0.014* | -0.037*** | -0.008 | 0.003 | 0.009 | 0.028*** | 0.018** | 0.220*** | 1 | | | | | |
| *TobinQ* | -0.113*** | -0.084*** | -0.091*** | -0.083*** | -0.004 | -0.024*** | -0.020** | -0.080*** | -0.430*** | 0.278*** | 0.078*** | 1 | | | | |
| *Size* | 0.366*** | 0.300*** | 0.311*** | 0.285*** | 0.065*** | 0.086*** | 0.092*** | 0.228*** | 0.244*** | 0.013 | 0.030*** | -0.386*** | 1 | | | |
| *SOE* | -0.005 | 0.067*** | 0.078*** | 0.078*** | 0.028*** | 0.082*** | 0.079*** | -0.014* | 0.338*** | -0.138*** | -0.082*** | -0.259*** | 0.342*** | 1 | | |
| *Age* | -0.004 | 0.003 | 0.016** | 0.013* | -0.021*** | 0.007 | 0.014* | -0.002 | 0.348*** | -0.154*** | -0.062*** | -0.197*** | 0.320*** | 0.231*** | 1 | |
| *Partner_RD* | 0.241*** | 0.310*** | 0.303*** | 0.282*** | 0.016** | 0.038*** | 0.049*** | 0.454*** | 0.021*** | 0.091*** | -0.041*** | -0.079*** | 0.239*** | 0.037*** | 0.059*** | 1 |
| *Partner_Lev* | 0.015** | 0.049*** | 0.071*** | 0.050*** | 0.007 | 0.063*** | 0.051*** | 0.005 | 0.316*** | -0.280*** | -0.019** | -0.360*** | 0.391*** | 0.355*** | 0.306*** | 0.059*** |
| *Partner_ROA* | 0.097*** | 0.055*** | 0.035*** | 0.056*** | 0.034*** | 0.014* | 0.021*** | 0.142*** | -0.341*** | 0.509*** | 0.013* | 0.196*** | 0.016** | -0.137*** | -0.200*** | 0.125*** |
| *Partner_Growth* | 0.017** | -0.005 | 0.001 | -0.010 | -0.007 | 0.012 | 0.003 | 0.038*** | 0.019** | 0.141*** | 0.129*** | 0.029*** | 0.036*** | -0.067*** | -0.079*** | -0.013* |
| *Partner_Size* | 0.263*** | 0.226*** | 0.236*** | 0.216*** | 0.045*** | 0.110*** | 0.106*** | 0.315*** | 0.356*** | -0.032*** | -0.076*** | -0.410*** | 0.265*** | 0.358*** | 0.355*** | 0.391*** |
| *Partner_SOE* | -0.027*** | 0.050*** | 0.061*** | 0.057*** | 0.011 | 0.065*** | 0.057*** | -0.032*** | 0.319*** | -0.131*** | -0.071*** | -0.233*** | 0.293*** | 0.381*** | 0.420*** | 0.031*** |
| *Partner_age* | 0.015* | 0.011 | 0.025*** | 0.023*** | -0.018** | 0.002 | 0.012 | 0.013 | 0.345*** | -0.144*** | -0.067*** | -0.195*** | 0.317*** | 0.315*** | 0.230*** | 0.021*** |

TABLE IV
CORRELATION MATRIX (CONTINUED)

| ***VARIABLES*** | **17** | **18** | **19** | **20** | **21** | **22** |
|---|---|---|---|---|---|---|
| *Partner_Lev* | 1 | | | | | |
| *Partner_ROA* | -0.414*** | 1 | | | | |
| *Partner_Growth* | 0.01 | 0.228*** | 1 | | | |
| *Partner_Size* | 0.356*** | -0.004 | -0.008 | 1 | | |
| *Partner_SOE* | 0.351*** | -0.143*** | -0.073*** | 0.358*** | 1 | |
| *Partner_age* | 0.377*** | -0.193*** | -0.067*** | 0.302*** | 0.425*** | 1 |

method to conduct this test. First, we examined the impact of the independent variable (i.e., R&D partners' network position) on the dependent variable (focal firm innovation). As shown in Column (4) in *Table V* above, we found a positive and significant effect between R&D partners' network position and focal firm innovation.

Second, following Baron and Kenny [89], we assessed the impact of the independent (i.e., R&D partners' network position) variable on the mediating variable (knowledge spill-in). As shown in Columns (1)-(3) in *Table V*, the relationship between R&D partners' network position and knowledge spill-in was also positive and significant.

Third, we tested the impact of mediating variable (knowledge spill-in) on the dependent variable (i.e., focal firm innovation). The results in *Table VI* show that there is also a positive and significant relationship between knowledge spill-in and focal firm innovation. In addition, in Columns (4) - (6) in *Table VI,* we estimated the full regression model with both R&D partners' network position and knowledge spill-in, which is used to test whether knowledge spill-in plays a fully or partially mediating role [89]. The results show that R&D partners' network centrality and structural holes still have a significant and positive effect on focal firm innovation, a finding which indicates that knowledge spill-in partially mediates the relationship between the R&D partners' network position and the focal firm's innovation performance.

TABLE VI
REGRESSION RESULTS OF KNOWLEDGE SPILL-IN ON FOCAL FIRM'S INNOVATION PERFORMANCE

| VARIABLES | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | *Inno_Pfm* | | | | | |
| *Knowlg_total* | 0.592*** | | | 0.592*** | | |
| | (0.010) | | | (0.010) | | |
| *Knowlg_direct* | | 0.633*** | | | 0.633*** | |
| | | (0.012) | | | (0.012) | |
| *Knowlg_clear* | | | 0.584*** | | | 0.583*** |
| | | | (0.012) | | | (0.012) |
| *Partner_C* | | | | 2.295*** | 2.249*** | 2.247*** |
| | | | | (0.726) | (0.653) | (0.672) |
| *Partner_SH* | | | | 0.585*** | 0.561*** | 0.588*** |
| | | | | (0.089) | (0.090) | (0.091) |
| *RD* | 0.218*** | 0.233*** | 0.238*** | 0.219*** | 0.234*** | 0.239*** |
| | (0.011) | (0.011) | (0.012) | (0.011) | (0.011) | (0.012) |
| *Lev* | 0.150 | 0.138 | 0.182* | 0.155* | 0.142 | 0.187* |
| | (0.093) | (0.095) | (0.097) | (0.093) | (0.094) | (0.096) |
| *ROA* | 0.808*** | 0.884*** | 0.764*** | 0.807*** | 0.884*** | 0.763*** |
| | (0.243) | (0.247) | (0.250) | (0.242) | (0.245) | (0.249) |
| *Growth* | -0.024 | -0.038 | -0.003 | -0.028 | -0.041 | -0.006 |
| | (0.026) | (0.026) | (0.027) | (0.026) | (0.026) | (0.027) |
| *TobinQ* | -0.030*** | -0.030*** | -0.029*** | -0.031*** | -0.031*** | -0.030*** |
| | (0.007) | (0.007) | (0.008) | (0.007) | (0.007) | (0.008) |
| *Size* | 0.168*** | 0.178*** | 0.200*** | 0.164*** | 0.174*** | 0.196*** |
| | (0.017) | (0.017) | (0.018) | (0.017) | (0.017) | (0.017) |
| *SOE* | 0.078* | 0.100** | 0.083* | 0.065 | 0.087** | 0.070 |
| | (0.043) | (0.044) | (0.045) | (0.043) | (0.043) | (0.044) |
| *Age* | -0.023*** | -0.023*** | -0.025*** | -0.022*** | -0.022*** | -0.024*** |
| | (0.004) | (0.005) | (0.005) | (0.004) | (0.004) | (0.005) |
| *Partner_RD* | 0.036*** | 0.036*** | 0.043*** | 0.034*** | 0.034*** | 0.041*** |
| | (0.010) | (0.010) | (0.010) | (0.010) | (0.010) | (0.010) |
| *Partner_Lev* | -0.053 | -0.067 | -0.057 | -0.043 | -0.056 | -0.046 |
| | (0.091) | (0.093) | (0.094) | (0.090) | (0.092) | (0.093) |
| *Partner_ROA* | 0.834*** | 0.951*** | 0.786*** | 0.857*** | 0.970*** | 0.808*** |
| | (0.242) | (0.246) | (0.247) | (0.240) | (0.244) | (0.245) |
| *Partner_Growth* | 0.014 | 0.006 | 0.019 | 0.013 | 0.006 | 0.018 |
| | (0.025) | (0.026) | (0.026) | (0.025) | (0.026) | (0.026) |
| *Partner_Size* | -0.010 | -0.010 | -0.009 | -0.017 | -0.017 | -0.016 |
| | (0.014) | (0.014) | (0.015) | (0.014) | (0.014) | (0.014) |
| *Partner_SOE* | -0.115*** | -0.124*** | -0.092** | -0.101** | -0.110** | -0.078* |
| | (0.043) | (0.044) | (0.044) | (0.042) | (0.043) | (0.044) |
| *Partner_age* | 0.016*** | 0.015*** | 0.015*** | 0.015*** | 0.014*** | 0.014*** |
| | (0.004) | (0.004) | (0.005) | (0.004) | (0.004) | (0.004) |
| *Year* | Yes | Yes | Yes | Yes | Yes | Yes |
| *Industry* | Yes | Yes | Yes | Yes | Yes | Yes |
| *Observations* | 15,573 | 15,573 | 15,573 | 15,573 | 15,573 | 15,573 |
| *Adj_$R^2$* | 0.521 | 0.502 | 0.488 | 0.523 | 0.504 | 0.490 |

Note: Robust standard errors in parentheses. *** p<.01, ** p<.05, * p<.10.

Following Zhao, et al. [90], we also used the bootstrap method to test the mediation effect of knowledge spill-in, and set the number of self-sampling to 1,000. *Table VII* summarizes the test results using different measures for knowledge spill-in. It shows neither the direct effect nor the mediation effect contains 0 in the 95% confidence interval. This result indicates that knowledge spill-in has an intermediary effect on the R&D partners' network position and firm innovation. This finding further confirms the robustness of the data results.

TABLE VII
MEDIATION EFFECT OF KNOWLEDGE SPILL-IN USING THE BOOTSTRAP METHOD

| ***Mediator: Knowlg_total*** | Coef. | Std. Err. | z | P>\|z\| | [95% Conf. Interval] | |
|---|---|---|---|---|---|---|
| _bs_1: r(ind_eff) | 0.209 | 0.060 | 3.457 | 0.000 | 0.093 | 0.324 |
| _bs_2: r(dir_eff) | 4.354 | 0.744 | 5.850 | 0.000 | 2.896 | 5.812 |
| ***Mediator: Knowlg_direct*** | Coef. | Std. Err. | z | P>\|z\| | [95% Conf. Interval] | |
| _bs_1: r(ind_eff) | 0.285 | 0.070 | 4.085 | 0.000 | 0.097 | 0.473 |
| _bs_2: r(dir_eff) | 4.485 | 0.705 | 6.360 | 0.000 | 3.103 | 5.867 |
| ***Mediator: Knowlg_clear*** | Coef. | Std. Err. | z | P>\|z\| | [95% Conf. Interval] | |
| _bs_1: r(ind_eff) | 0.447 | 0.053 | 8.432 | 0.000 | 0.159 | 0.734 |
| _bs_2: r(dir_eff) | 3.993 | 0.763 | 5.230 | 0.000 | 2.496 | 5.489 |

*Moderating effect of relationship duration*

We then examined the influence of the moderating factors, as indicated in H4 and H5; that is, the moderating effect of the relationship duration. Specifically, as shown in Columns (1)-(3) in *Table VIII*, we added the interaction term of the independent variable (i.e., R&D partners' network position) and relationship duration. The coefficients for the moderating effect of the relationship duration on the R&D partners' network centrality—knowledge spill-in relationship were 0.550, 0.531 and 0.525, which are significant at 5%, 5% and 1% levels, respectively. The coefficients for the moderating effect of the relationship duration on the R&D partners' structural holes—knowledge spill-in relationship were also positive and significant. Thus, our preliminary results suggest that relationship duration (a certain time range) plays a positive moderating effect.

In Columns (4)-(6) of *Table VIII*, we added the interaction term of the independent variable and the quadratic term of relationship duration (*$Duration^2$*). The coefficients for the moderating effect of quadratic term of relationship duration on the R&D partners' network centrality—knowledge spill-in relationship were -0.325, -0.478 and-0.433, which are significant at 5%, 10% and 1% levels, respectively. The above results indicate that an excessive relationship duration plays a negative effect, and also suggest that relationship duration plays an inverted U-shaped moderating role between R&D partners' network centrality and knowledge spill-in. *This finding supports Hypothesis 4.*

The coefficients for the moderating effect of quadratic term of relationship duration on the R&D partners' structural holes—knowledge spill-in relationship were -0.344, -0.273 and -0.128, which are significant at 10%, 1% and 5% levels, respectively. The above results also indicate that relationship duration plays an inverted U-shaped moderating role between

R&D partners' structural holes and knowledge spill-in. *These findings thus confirm Hypothesis 5*.

TABLE VIII
THE MODERATING EFFECT OF THE RELATIONSHIP DURATION BETWEEN R&D PARTNER NETWORK POSITIONS AND KNOWLEDGE SPILL-IN

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| ***VARIABLES*** | *Knowlg _total* | *Knowlg _direct* | *Knowlg _clear* | *Knowlg _total* | *Knowlg _direct* | *Knowlg _clear* |
| *Partner_C X* | 0.550** | 0.531** | 0.525*** | 0.423** | 0.401 | 0.584* |
| *Duration* | (0.256) | (0.232) | (0.165) | (0.207) | (0.314) | (0.799) |
| *Partner_SH X* | 0.155*** | 0.137** | 0.142** | 0.279 | 0.282* | 0.109* |
| *Duration* | (0.022) | (0.056) | (0.073) | (0.238) | (0.153) | (0.057) |
| *Partner_C* | 2.442** | 2.001** | 2.442** | 2.096** | 1.474* | 1.765* |
| | (0.974) | (0.822) | (0.974) | (0.984) | (0.811) | (0.983) |
| *Partner_SH* | 0.171* | 0.143* | 0.171* | 0.089 | 0.086 | 0.130 |
| | (0.094) | (0.079) | (0.094) | (0.119) | (0.099) | (0.108) |
| *Duration* | 0.177*** | 0.145*** | 0.177*** | 0.395** | 0.130 | 0.481** |
| | (0.023) | (0.017) | (0.023) | (0.198) | (0.163) | (0.199) |
| *Partner_C X* | | | | -0.325** | -0.478* | -0.43*** |
| *Duration$^2$* | | | | (0.156) | (0.254) | (0.122) |
| *Partner_SH ** | | | | -0.344* | -0.27*** | -0.128** |
| *Duration$^2$* | | | | (0.184) | (0.059) | (0.107) |
| *Duration$^2$* | | | | -0.300** | -0.145 | -0.308* |
| | | | | (0.149) | (0.385) | (0.162) |
| *RD* | 0.157*** | 0.123*** | 0.124*** | 0.156*** | 0.123*** | 0.124*** |
| | (0.009) | (0.008) | (0.007) | (0.009) | (0.008) | (0.007) |
| *Lev* | 0.047 | 0.069 | -0.009 | 0.040 | 0.069 | -0.018 |
| | (0.077) | (0.067) | (0.065) | (0.077) | (0.067) | (0.064) |
| *ROA* | -0.070 | -0.195 | 0.000 | -0.070 | -0.186 | -0.003 |
| | (0.167) | (0.143) | (0.134) | (0.167) | (0.143) | (0.134) |
| *Growth* | -0.021 | 0.000 | -0.058*** | -0.020 | 0.001 | -0.056*** |
| | (0.018) | (0.016) | (0.013) | (0.018) | (0.016) | (0.013) |
| *TobinQ* | 0.021*** | 0.020*** | 0.021*** | 0.021*** | 0.020*** | 0.021*** |
| | (0.005) | (0.005) | (0.004) | (0.005) | (0.005) | (0.004) |
| *Size* | 0.209*** | 0.181*** | 0.158*** | 0.211*** | 0.182*** | 0.160*** |
| | (0.016) | (0.014) | (0.013) | (0.016) | (0.014) | (0.013) |
| *SOE* | 0.158*** | 0.116*** | 0.153*** | 0.159*** | 0.118*** | 0.153*** |
| | (0.036) | (0.032) | (0.030) | (0.036) | (0.032) | (0.030) |
| *Age* | -0.011** | -0.010*** | -0.009** | -0.012** | -0.011*** | -0.010** |
| | (0.005) | (0.004) | (0.004) | (0.005) | (0.004) | (0.004) |
| *Partner_RD* | 0.016* | 0.015** | 0.006 | 0.017** | 0.014** | 0.006 |
| | (0.008) | (0.007) | (0.007) | (0.008) | (0.007) | (0.007) |
| *Partner_Lev* | -0.061 | -0.042 | -0.054 | -0.055 | -0.043 | -0.046 |
| | (0.075) | (0.065) | (0.063) | (0.075) | (0.065) | (0.063) |
| *Partner_ROA* | -0.278* | -0.436*** | -0.196 | -0.291* | -0.443*** | -0.209 |
| | (0.160) | (0.137) | (0.130) | (0.160) | (0.137) | (0.130) |
| *Partner_Growth* | -0.008 | 0.003 | -0.017 | -0.008 | 0.004 | -0.016 |
| | (0.019) | (0.017) | (0.016) | (0.019) | (0.017) | (0.016) |
| *Partner_Size* | 0.019 | 0.018 | 0.018 | 0.019 | 0.018 | 0.018 |
| | (0.014) | (0.012) | (0.011) | (0.014) | (0.012) | (0.011) |
| *Partner_SOE* | -0.019 | -0.008 | -0.059* | -0.020 | -0.010 | -0.059* |
| | (0.036) | (0.032) | (0.031) | (0.036) | (0.032) | (0.031) |
| *Partner_age* | 0.005 | 0.006 | 0.006 | 0.006 | 0.006 | 0.007* |
| | (0.005) | (0.004) | (0.004) | (0.005) | (0.004) | (0.004) |
| *Control* | Yes | Yes | Yes | Yes | Yes | Yes |
| *Year* | Yes | Yes | Yes | Yes | Yes | Yes |
| *Industry* | Yes | Yes | Yes | Yes | Yes | Yes |
| *Observations* | 15,573 | 15,573 | 15,573 | 15,573 | 15,573 | 15,573 |
| *Adj_$R^2$* | 0.351 | 0.319 | 0.270 | 0.352 | 0.319 | 0.272 |

Note: Robust standard errors in parentheses. *** p<.01, ** p<.05, * p<.10.

As the example in Column 6 in *Table VIII* shows, we plotted the moderating effects of relationship duration in Figures 6 and 7. Figure 6 shows the moderating effect of duration between R&D partners' network centrality and knowledge spill-in. The results indicate that relationship duration plays an inverted U-shaped moderating role. Similarly, Figure 7 indicates that relationship duration plays an inverted U-shaped moderating role between R&D partners' structural holes and knowledge spill-in.

## C. Robustness Tests

We performed a series of tests to validate our findings, including endogeneity assessments, varied modeling approaches, and other robustness checks. None of these tests altered our primary results. The robustness test results are available from the authors upon request.

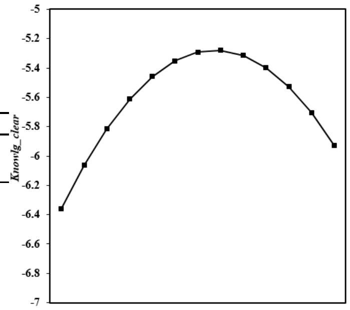


Fig. 6. The moderating effect of duration between R&D partners' centrality and knowledge spill-in

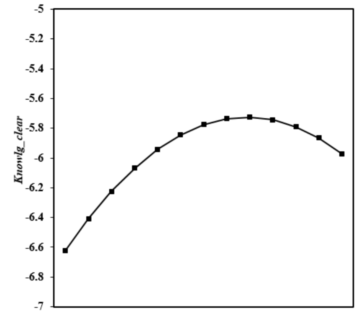


Fig. 7. The moderating effect of duration between partners' structural holes and knowledge spill-in

## VI. DISCUSSIONS

Overall, our data supported our proposed hypotheses. First, the R&D partners' network positions (both structural holes and network centrality) were positively associated with knowledge spill-in to focal firms. Second, knowledge spill-in was positively associated with focal firms' innovation performance. Third, relationship duration between R&D partners and focal firms had an inverted U-shaped moderating effect on the relationship between R&D partners' network positions and knowledge spill-in, and it should be noted that Figure 9 only shows the interaction terms of the independent variable and the quadratic term of relationship duration.

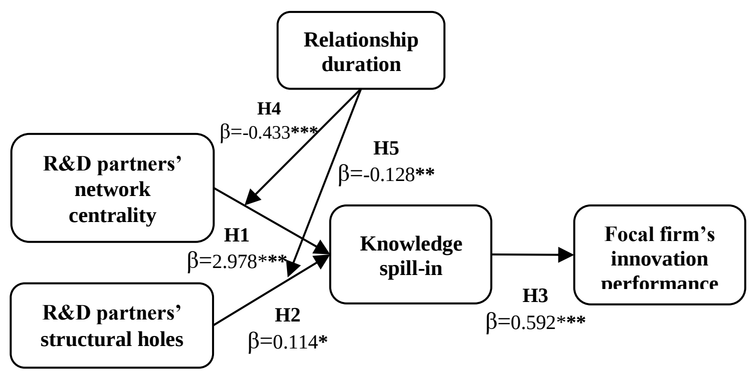


Fig.9. Regression results

## A. Theoretical Implications

This study contributes to literature in three ways. First, in shifting from the ego network perspective to the alter network perspective, we highlight the role of second-order social capital in influencing a firm's innovation performance. Our research findings support assumptions about the positive externalities of social capital in R&D partnerships. By occupying structural holes or having higher network centrality, R&D partners function as a knowledge brokers or knowledge hubs, thus shaping knowledge flows and diffusion in the networks. Firms that are connected with R&D partners with superior network positions are more likely to gain additional knowledge benefits. As Galunic, et al. [18] have explained, superior network positions such as structural holes not only create competitive advantages for themselves, but also create value for others. The information and knowledge they have access to can flow into the connected ones and thus improve others' knowledge pools and boost problem-solving and innovation.

Second, we provide a more nuanced understanding of *how* firms are more likely to benefit from R&D collaborations through a knowledge spill-in perspective. While prior research has provided extensive evidence on the positive impact of R&D collaboration on a firm's innovation performance, this study identifies the mediating role of knowledge spill-in in the relationship between R&D network position and a focal firm's innovativeness. Moreover, it reveals the underlying mechanism of how the R&D partners' positional advantage can be transformed into the focal firm's innovation advantage. This finding contributes to the knowledge-based view of the firm and provides a deeper understanding of knowledge spill-in in inter-firm networks.

Third, the identification of the moderation role of relationship duration addresses *when* firms are more likely to benefit from R&D collaborations. The inverted U-shaped moderating role of relationship duration reinforces the dynamic nature of R&D partnerships and highlights the importance of strategically managing collaborative relations. Prior research has emphasized the need for more analyses of R&D collaboration from a dynamic point of view [12]. Our research findings partially reveal the importance of indirect ties and the need for the ongoing reconfiguration of networks [91]. The relationship duration or the length of partnership can be a double-edge sword. It can strengthen or weaken the knowledge benefits from second-order social capital. A relatively short relationship duration facilitates knowledge spillover between firms. But firms should be cautious about extensively long relationships with certain partners, as they may result in a "small world network" and strong path dependence, which can potentially hinder diversified knowledge spillover and a firm's innovation performance.

### *B. Managerial and Practical Implications*

This study has several managerial and practical implications. First, the positive relationships between the second-order social capital, knowledge spill-in, and a firm's innovation performance confirm that resource heterogeneity is a source of performance differences across firms. Such resources not only include the direct resources of the focal firm, but also the resource profiles of the R&D partners. To maximize the benefits in collaborative R&D partnership, firms should consider, strategically speaking, who they partner with. Firms should not only consider R&D partners' size, type, existing knowledge, and expertise, but also their partners' network positions. When firms collaborate with R&D partners who are located at the central position or the brokerage position across structural holes, they are more likely to gain additional benefits due to the positive externality of social capital [92]. In the selection of R&D partners, firms should evaluate the strategic network position as it has the potential to increase access to new knowledge and improve incoming knowledge flows to the focal firm. However, we also found that for firms with superior network positions themselves, the impacts of the R&D partners' network on the focal firm's performance are stronger. This finding implies that the firms who are more likely to benefit from second-order social capital are the ones who are well-connected themselves.

Second, the inverted U-shaped moderation effect of relationship duration on the relationship between R&D partners' network positions and knowledge spill-in to the focal firm suggests that firms should maintain an appropriate relationship with their R&D partners to benefit more from the knowledge spilled into the firms. In general, the longer the relationship, the more knowledge spill-in to the focal firms from the R&D partners' network position. Prior research has found that the magnitude of the impact increases over time. For example, in their study of knowledge spillovers in supply chains, Isaksson, et al. [75] found that the relationship duration between buyers and suppliers amplified the effect of knowledge spillovers. The influence of buyer's technological innovation had little or no impact on suppliers' innovativeness during the first year of the partnership; however, it became statistically significant from the second year onwards. However, there is a potential cost; an extensively long relationship with certain R&D partners can bring stagnation of new knowledge spill-in, which in turn harm a firm's innovation performance. Thus, when firms seek partnerships for innovation projects, they should consider the time dimension as knowledge spill-in requires a significant amount of time to happen. In sum, firms should be more careful in the selection of their R&D partners and assess the potential impact of time in any partnership changes.

## VII. CONCLUSIONS

This study adopted the "alter" approach to investigate inter-firm networks. More specifically, it has examined the i of second-order social capital and consequent impacts on focal firms. In contrast to prior studies that have focused on the direct relationship between R&D network positions and focal firms' innovation performance, this study has identified the underlying mechanisms by highlighting the mediator of knowledge spill-in. We found that the positive externalities of second-order social capital in R&D networks occur mainly through incoming knowledge spillover; i.e., knowledge spill-in. R&D partners who have advantageous network positions, such as centrality and structural holes, have greater incoming knowledge flow into the focal firm, which in turn improves the firm's innovation capability. In addition, we found that the length of the relationship (duration) between the focal firm and the R&D partners moderates the impacts of second-order social capital on knowledge spill-in. Longer and more established relationships increase the chances of incoming knowledge flows from R&D network positions. This study contributes to ongoing conversations on the knowledge-based view of understanding R&D collaborations. It also sheds light on the research on second-order social capital and provides empirical evidence of its positive impacts on focal firms' performance.

However, we acknowledge there are limitations in this study which should be addressed in future studies. For example, we only focused on one aspect of network effects, i.e., the network position of R&D partners, and did not examine the effect of network size or network contents. According to Schilling and Phelps [93], the network size and average path length have an impact on information diffusion. The more firms that can be reached by any path from the R&D partners, the more knowledge that the R&D partners can access. As a result, collaborating with the R&D partners who have a large network size will potentially increase the knowledge spill-in from the R&D partners to the focal firm.

Future research should also consider the interaction effects of network position and network size on a firm's innovation performance. In a study of firms' ego networks, Rodan and Galunic [94] found that the significant impact of network size on a firm's managerial performance and innovativeness did not hold when network position was included in the model. Whether such an effect holds in the alter networks remains unclear. Moreover, it is worth investigating how different types of network positions influence homogeneous knowledge spill-in and heterogeneous knowledge spill-in and whether different types of knowledge spill-result in different innovation outcomes, such as exploratory innovation and exploitative innovation. In addition, other than knowledge, resources such as human capital, financial capital, and technological capital are also critical in R&D alliances. Future research may consider adopting a broader view of network resources [60] or network capital to examine the investments and exchange of resources by firms in R&D alliances. In addition, this study only collected data from a single market. Using panel data may also result in the possibility of omitted variable bias or endogeneity. Therefore, we encourage future studies to diversify the data source and further examine the similarities and differences across countries.

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