Social network and radical innovation: evidence from the U.S. pharmaceutical and biotechnology industry

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CHAPTER 2

Collaboration networks and radical innovation: Two faces of tie strength and structural holes

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Author contributions:

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Abstract: This paper studies the relationship between the structure of corporate R&D collaboration networks and radical innovation, more specifically, how tie strength and structural holes collectively affect innovation radicalness at a location within an innovating firm. We identified 16,011 inventors' locations of the 93 most innovative U.S. pharmaceuticals and biotechnology companies on the EU Industrial R&D Investment Scoreboard. We tracked their patents from 2001 to 2013 and constructed a panel dataset for analysis. Using firm-location fixed effect models, we found that tie strength has a negative effect on innovation radicalness, and this negative effect is stronger when the network is cohesive. This suggests that weak ties have informational advantages for radical innovation, which are more pronounced when there is network cohesion to mitigate the relational disadvantages of weak ties. We also found that structural holes have a negative effect on innovation radicalness when tie strength is weak but a positive effect when tie strength is strong. This suggests that strong ties are needed for mobilizing the informational advantages of structural holes.

Keywords: Collaboration network, Multinational R&D, Radical innovation, Tie strength, Structural hole

2.1 Introduction

Schumpeter (1942) considered firm innovation as the "fundamental impulse that sets and keeps the capitalist engine in motion" and coined the term "creative destruction" that "revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one." However, innovations vary in the degree of "destruction" that they bring, ranging from run-of-the-mill innovation that bring incremental changes to existing technologies to radical innovation that break from and make obsolete existing cognitive framework, technological trajectories, and organizational structures (Anderson & Tushman, 1990; Chang et al., 2012; Delgado-Verde et al., 2016; Dosi, 1982; Henderson, 1993; Henderson & Clark, 1990; Kobarg et al., 2019; Tushman & Anderson, 1986; Utterback, 1996; Verhoeven et al., 2016). Radical innovation has received much attention from innovation scholars. Prior studies have extensively investigated technological origins of radical innovation, as well as its economic implications for the innovating company and industry (Capponi et al., 2022; Rosenkopf & Nerkar, 2001; Schoenmakers & Duysters, 2010; Simms et al., 2021; Ukobitz & Faullant, 2022). These studies have contributed many insights for understanding radical innovation. However, we know relatively little about the social determinants of radical innovation in the organizational and social environment. In this paper, we explore how network structure affects radical innovation.

The creativity and social network literatures have long highlighted the importance of network structure for individual and organizational creative performance (Amabile, 1983; Drazin et al., 1999; Ford, 1996; Perry-Smith & Shalley, 2003; Perry-Smith & Shalley, 2014; Sosa, 2011; Woodman et al., 1993). Some researchers highlight the benefits of weak ties and structural holes, while others suggest advantages of strong ties and network cohesion for radical innovation (Ahuja, 2000a; Burt, 1992; Coleman, 1988; Fleming et al., 2007; Granovetter, 1973; Nahapiet & Ghoshal, 1998; Perry-Smith, 2006; Rost, 2011; Tortoriello & Krackhardt, 2010). In this paper, we separate two faces of weak ties and structural holes: their informational advantages in accessing the diverse knowledge that is needed for radical innovation, and their relational disadvantages linked to a weaker shared understanding and trust. In turn, the informational advantages of structural holes can be mobilized if there are strong ties for mitigating the relational disadvantages of structural holes. Similarly, network cohesion is needed for mobilizing informational advantages of weak ties.

We study the network effect in the context of multinational corporations' internal R&D collaboration networks. Overseas R&D is playing an increasingly important role in the R&D networks of multinationals, and the competitiveness of the firm relies on its ability to coordinate its R&D activities across the globe (Alcácer & Zhao, 2012; Almeida & Phene, 2004; Belderbos et al., 2021; Du et al., 2022; Kuemmerle, 1997). While prior studies have systematically investigated drivers of R&D location decisions and strategies for coordinating subsidiaries, it has not yet studied how the network structure affects radical innovation at a particular R&D location.

Our study focuses on the 93 most innovative U.S. pharmaceuticals and biotechnology companies according to the EU Industrial R&D Investment Scoreboard. We track their patenting activities from 2001 and 2013. We construct their collaboration networks where nodes are locations of inventors and edges are co-patenting activities. We build a panel dataset consisting of 19,343 firm-location-year observations and fit fixed effect models to examine variations within firm-locations. We found (1) a negative effect of tie strength on radical innovation, (2) an insignificant effect of structural holes, and (3) a positive interaction effect between tie strength and structural holes.

The rest of this paper is organized as follows. In section 2, we review the literature on radical innovation and social networks. We also develop hypotheses concerning the effect of tie strength and structural holes on radical innovation. Section 3 provides a discussion of our data and methods. Using a panel dataset of observations from 2001 to 2013, we conduct empirical analyses to explore the relationship between network structures and radical innovation. In section 4, we present the results of our analyses. Implications and limitations of our findings are discussed in section 5.

2.2 Theory and hypotheses

2.2.1 Radical innovation

Interest in radical innovation dates back to Schumpeter (1934; 1942), who coined the term "creative destruction," a process that new innovation "revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one" (Schumpeter, 1942, p. 83). Schumpeter highlighted the destructive nature of innovation, while innovations may vary in the intensity of destruction that they bring. Subsequent studies have further separated radical innovation from incremental or run-of-the-mill innovation. For example, Henderson and Clark (1990) defined radical innovation as innovation that disrupts both existing components and architecture. Anderson and Tushman (1990) distinguished between competence-enhancing and competence-destroying technological discontinuities. Henderson (1993) viewed radical innovation as innovation that obsoletes a company's existing information filters and organizational procedures. Ahuja and Morris Lampert (2001)defined radical or breakthrough inventions as foundational inventions that serve as the basis for many subsequent technical developments. Dahlin and Behrens (2005) emphasized three defining features of radical innovation: novel, unique, and having a major impact on future technology. Funk and Owen-Smith (2017) and Chen et al. (2021) viewed radical innovations as those that destabilize existing technology trajectories or reshape the network of technology interlinkages by shifting future inventors' attention away from the knowledge on which the focal patent builds. Following this line of literature, we view radical innovation as innovation which brings intensive destruction and changes technology trajectories.

Prior studies of radical innovation have extensively investigated its economic impact (Hsieh et al., 2018; Rosenkopf & Nerkar, 2001), technological origins (Capponi et al., 2022; Schoenmakers & Duysters, 2010), response strategies (Matthews et al., 2022; Ukobitz & Faullant, 2022), and methods for adapting business models after disruption (Bourreau et al., 2012; Cozzolino et al., 2018; D'Ippolito et al., 2019; Simms et al., 2021). These studies have contributed many insights for understanding radical innovation. However, we know relatively little about the social determinants of radical innovation in the organizational and social environment. In particular, in the context of corporate R&D networks, how properties of collaboration network affect the likelihood of producing radical innovations. Answers to this question will help us to explain why radical innovation emerge in some place but not others, as well as informing innovation strategy about how to create a favorable collaboration network for radical innovation. This paper focuses on two network properties: tie strength and structural hole.

2.2.2 Informational advantage of weak tie for radical innovation

Mark Granovetter (1973) defined tie strength as: “a (probably linear) combination of the amount of time, the emotional intensity, the intimacy (mutual confiding), and the reciprocal services which characterize the tie”. Since Granovetter’s seminal work, tie strength has attracted a lot of attention. Scholars have investigated its effects on various outcomes such as career advancement (Bian, 1997; Granovetter, 1995; Montgomery, 1992; Yakubovich, 2005), knowledge transfer (Hansen, 1999; Messeni Petruzzelli et al., 2010; Reagans & McEvily, 2003; Tortoriello et al., 2012), and knowledge creation (Levin et al., 2011; McFadyen & Cannella Jr, 2004; McFadyen et al., 2009; Perry-Smith, 2006; Perry-Smith & Shalley, 2003; Perry-Smith & Shalley, 2014; Smith et al., 2005; Sosa, 2011; Tortoriello & Krackhardt, 2010; Wang, 2016). Building on this line of research, we develop theory and hypotheses about how tie strength affects the creation of radical innovation.

The central argument in favor of weak ties pertains to its advantage over strong ties in accessing non-redundant information (Granovetter, 1982; Granovetter, 1973; Uzzi, 1996; Uzzi & Spiro, 2005). Similar actors tend to be interconnected with one another by strong ties, and therefore an actor is likely to acquire similar information from others through strong ties (Festinger et al., 1950; Granovetter, 1973; Katz & Lazarsfeld, 2017). In other words, information circulated across a network through strong ties is prone to be redundant since actors inside this social circle tend to recycle ideas. In contrast, weak ties usually serve as information bridges between unconnected communities. Therefore, such ties provide channels for accessing diverse knowledge which originates from outside actors’ direct social circle.

Furthermore, access to diverse knowledge is an important condition for generating creative ideas. The creativity literature highlights that one important source of novelty constitutes of new combinations of pre-existing knowledge components (Mednick, 1962; Nelson & Winter, 1982; Schumpeter, 1939). Accordingly, exposure to diverse knowledge provides opportunities for identifying new connections and generating novel ideas. This has the potential to destabilize existing technology trajectories. In addition, diverse knowledge enables a broader and more thorough search through problem- and solution- spaces, leading to better solutions and inventions (Page, 2007; Simonton, 1999, 2003).

Prior studies on tie strength and creativity have shown that actors with more weak ties are more adept at generating novel ideas (Baer, 2010; Perry-Smith, 2006; Perry-Smith & Shalley, 2003; Perry-Smith & Shalley, 2014; Zhou et al., 2009). For example, Perry-Smith and Shalley (2014) have shown that weak ties foster creativity by providing access to disconnected actors and enhance the domain- or creativity-relevant knowledge. We expect that access to non-redundant knowledge is of critical importance for developing radical innovations, because non-redundant knowledge provides the foundation for creating new components and connections in a unique way that deviates from existing ways of thinking. Accordingly, weak ties have the potential to make obsolete existing technology trajectories and we hypothesize that:

Hypothesis 1. Tie strength has a negative effect on innovation radicalness.

2.2.3 Informational advantage of structural hole for radical innovation

Different from tie strength, the concept of structural hole proposed by Burt (1992) focuses on the absence of network ties between actors in a network. More specifically, an egocentric network is rich in structural holes if the ego's contacts are not themselves interconnected. Individuals with contact networks that are rich in structural holes are at an advantageous position, because structural holes provide "an opportunity to broker the flow of *information* between people, and *control* the projects that bring together people from opposite sides of the hole" (Burt, 2000, p. 353). Studies have observed benefits of structural holes for career advancement (Burt, 1992; Seibert et al., 2001), generation of novel ideas (Burt, 2004; Fleming et al., 2007), and project performance (Soda et al., 2004; Zaheer & Soda, 2009). Building on this line of literature, we expect that structural holes are beneficial for developing radical innovations, due to the brokage advantage in gaining broader and earlier access to diverse knowledge.

Structural holes present informational advantages, more specifically, broader access to diverse knowledge, which is conducive to radical innovation. Prior studies have shown that information is unevenly spread and tends to be homogenous within communities (Burt, 1992; Burt, 2004). Considering the homophily tendency in network formation, that is, actors tend to develop relations with others like themselves (Burt, 1990; Burt, 1992; Fischer, 1982; Marsden, 1987; McPherson et al., 2001), information that can be accessed within an interconnected community tends to be redundant. However, information from outside the community can bring diversity and heterogeneity (Cohen & Levinthal, 1990; Kleinbaum & Tushman, 2007). Prior studies have shown that creative ideas often emerge when an actor moves information from one community to another or combines knowledge across communities (Burt, 2004; Geroski & Mazzucato, 2002; Menon & Pfeffer, 2003). Therefore, an actor who bridges structural holes can benefit from the difference between his or her contacts who are unconnected and belonging to different communities (Burt, 1992; Burt, 2004). Knowledge gained through unlinked contacts tends to be additive rather than overlapping, and an actor who occupies a structural hole position has an advantage in being exposed to different information, knowledge, and perspectives from either side of the hole (Ahuja, 2000b; Burt, 1992; Gulati et al., 2000; Hargadon & Sutton, 1997). This informational advantage of structural hole is beneficial for developing radical innovation, as diverse information offers opportunities for cross-fertilization of ideas and outside-the-box thinking.

In addition, an actor with connections across structural holes can have early access to diverse information before the average actor, providing an advantage of acting on the information early and controlling the flow of information across communicates (Burt, 2004). This early access also provides a competitive advantage for developing radical innovation. Taken together, we hypothesize that:

Hypothesis 2. Structural holes have a positive effect on innovation radicalness.

2.2.4 Relational disadvantage of weak tie and structural hole for radical innovation

While both weak ties and structural holes present informational advantages for radical innovation, they present challenges in mobilizing potential information resources. Accordingly, how tie strength and structural holes may affect innovation radicalness is not so straightforward. Both weak ties and structural holes are signifiers of low cognitive capital (i.e., shared codes, language, and narratives) and relational capital (i.e., trust, norms, obligations, and identification) (Nahapiet & Ghoshal, 1998), which present relational disadvantages for radical innovation. Without a common knowledge base between actors, actors may face cognition and communication challenges in exchanging fine-grained information and tacit knowledge for creative process (Hansen, 1999; Reagans & McEvily, 2003; Uzzi, 1996, 1997; Wen et al., 2021). In addition, without a high level of mutual trust and shared norms between actors, actors may face higher of coordination costs and opportunistic behavior (Krackhardt et al., 2003; Lin & Ensel, 1989; Obstfeld, 2005; Podolny & Baron, 1997). In summary, while weak ties and structural holes provide access to more diverse knowledge, they present challenges in transferring and integrating this knowledge for producing radical innovation.

Prior studies of tie strength have underscored the relational advantage of strong ties in fostering shared understandings, trust, and willingness to help (Granovetter, 1973; Hansen, 1999; Krackhardt et al., 2003; Reagans & McEvily, 2003; Uzzi, 1996, 1997). Empirical evidence has also been accumulated that strong ties facilitate the exchange of fine-grained information and in turn the creation of new ideas (Rost, 2011; Sosa, 2011; Tortoriello & Krackhardt, 2010). Similarly, social network studies have acknowledged relational disadvantages of structural holes. According to Coleman's (1988) social capital theory, network closure or cohesion (i.e. the absence of structural holes) is conducive to the production of social norms and sanctions, which in turn facilitates trust and cooperative behavior. Empirical evidence has also suggested that structural holes do not translate into organizational advantages without measures to mitigate the relational disadvantages (Rost, 2011; Tortoriello & Krackhardt, 2010). Studies have also attempted to reconcile these competing arguments regarding the effects of tie strength (McFadyen & Cannella Jr, 2004; McFadyen et al., 2009; Perry-Smith, 2006; Perry-Smith & Shalley, 2003; Wang, 2016) and structural holes (Gargiulo & Benassi, 2000; Obstfeld, 2005; Rost, 2011; Tortoriello & Krackhardt, 2010), by exploring more complex effect patterns or boundary conditions.

Both tie strength and structural holes exhibit two faces: informational advantages on the one hand and relational disadvantages on the other hand. To further understand how these two competing mechanisms collectively affect innovation radicalness, we explore the interaction effect between tie strength and structural hole. More specifically, although an egocentric network rich in structural holes presents advantages in accessing diverse knowledge, such diverse knowledge can be mobilized and integrated for radical innovation if there are strong ties to compensate for the relational disadvantages of structural holes (Rost, 2011; Tortoriello &

Krackhardt, 2010). In other words, tie strength magnifies the positive effect structural holes on innovation radicalness. Similarly, actors with an egocentric network rich in weak ties have problems in translating knowledge advantages into radical innovation, and network cohesion can help to mitigate the relational disadvantages of weak ties. In other words, network cohesion increases the positive effect of weak ties on radical innovation. Taken together, we hypothesize that:

> *Hypothesis 3. There is a positive interaction effect between tie strength and structural holes on innovation radicalness.*

2.3 Data and Methods

2.3.1 Data and sample

To test our hypotheses, we construct a unique panel dataset with information about firm R&D locations, their collaboration networks, and innovation outputs. We combine information from various sources. Our sampled firms are identified from the 2018 edition of the *EU Industrial R&D Investment Scoreboard*, which provides a list of companies with the largest R&D spending in the world. We restrict our analysis to firms from the U.S. pharmaceutical and biotechnology industry on this list for three reasons. First, innovation plays an essential role in the pharmaceutical and biotechnology industry since this industry is knowledge-intensive, which provides us an appropriate setting for this research. Previous research has shown that this industry is suitable and has already been used in many fields to study innovative activities (Hoang & Rothaermel, 2005; Tzabbar & Vestal, 2015). Second, one of the critical competitive strategies of pharmaceutical and biotechnology companies is to forge connections across networks that span different social and geographic spheres (Al-Laham et al., 2011) in order to access diverse knowledge and resources. This feature provides us a higher chance to observe collaborations in this industry. In particular, corporate R&D networks that span different geographic locations enable multinational corporations to integrate local knowledge with complementary resources residing elsewhere in the world (Alcácer & Zhao, 2012), which means it provides us a good opportunity to study geographically dispersed corporate R&D networks. Third, focusing on a specific industry can control for variances across different industry fields (Audia & Goncalo, 2007; Tzabbar & Vestal, 2015). Using a more homogeneous sample ensures that innovation outputs can be compared. 200 U.S. pharmaceutical and biotechnology firms from the *Scoreboard* have been included in the sample.

For measuring innovation radicalness as well as for characterizing collaboration networks, we rely on patent information. However, retrieving patents for each company is not a trivial task. There are diverse practices in firm patenting policies. For example, some companies always use the headquarters as the applicants (also known as assignees) even though the invention was developed in a subsidiary, while others use the subsidiary as the applicant. Furthermore, the name of a company's subsidiary may not display any connection with the name of the whole company. Therefore, identifying all the names of subsidiaries is critical for retrieving all patents of a company and ensuring measurement quality. For our 200 sampled companies, we manually retrieved names of all subsidiaries listed in Exhibit 21 of the annual report on Form 10-K filed by these firms from 2009 to 2018 with the U.S. Securities and Exchange Commission (SEC). According to the Regulation S-K of the SEC, companies are required to report all of their subsidiaries, unless the unnamed subsidiaries are viewed as a single subsidiary and do not make up a significant subsidiary as of the end of the year covered by the report. Since our study focuses on R&D collaboration networks across a firm's locations, we excluded 107 firms without subsidiaries. After merging the data, our sample contains 16,011 unique subsidiaries belonging to 93 firms.

To extract the patents of the firms in our sample from the patent database (PATSTAT), we tried to match the names of the companies presented in the SEC database with the names of patent applicants appearing in the PATSTAT database. The 2019 Autumn version of PATSTAT was used. Name searching and cleaning strategies are applied to standardize the names. To do so, we identified strings that start with harmonized names of a company's subsidiary, strings containing the harmonized name of a subsidiary, and strings containing characteristics substrings that could identify a company's subsidiary. All found strings are manually checked against the original applicant's name and the three harmonized name versions ('doc_std_name', 'psn_name' and 'han_name') that are available in the PATSTAT database. In the next step we compared the names we found with the harmonized subsidiary names. The comparison was done using a 3-gram algorithm, that uses sliding windows of three-character strings. The algorithm provides an indicator that shows the similarity between the subsidiary or company name and an applicant's name. Only strings with a matching percentage of over 70% were considered to be potential matches. As a final step the results of the matching process were manually checked, and only a few match errors were found. We were looking for granted patents held by the firms in our sample, for which the patent applications were filed between 2001 to 2013 at United States Patent and Trademark Office (USPTO), the European Patent Office (EPO), or the World Intellectual Property Organization (WIPO).

We then aggregate patents at the location level, and inventor addresses are used to conjecture the locations of companies' innovative activities. Considering that subsidiaries often use the headquarters' address as the applicant address instead of the subsidiary's address when applying for a patent, inventor addresses are more likely to represent the real geographic origin of the patented inventions than applicant addresses (Belderbos et al., 2017; Deyle & Grupp, 2005). Addresses in the patent database are messy, and we link patent data to the geocoding of worldwide patent data developed by De Rassenfosse et al. (2019). De Rassenfosse et al. (2019) combined multiple data sources for identifying geographic coordinates for inventor and applicant locations and also provided clean information about corresponding countries, regions and cities. This dataset covers all PATSTAT patents in our studied time period. We use the fine-grained city level information for R&D locations of a firm's R&D network. For example, these cities include London (UK) and Berlin (Germany). The city level in the United States corresponds to counties, for example, Middlesex in Massachusetts and Santa Clara in California.

Furthermore, the same technological invention often is patented at multiple offices, so we use patent family according to the DOCDB definition (Martínez, 2011), instead of single patents, following the field convention. Building on the data of patent families, we construct our final dataset for analysis at the location-time level. For each location, we construct our variables using patent families in a 3-year moving time window. In other words, the location *i* at time point *t*, the variables are constructed using patent families with the earliest filing date in the three years from year *t-2* to year *t*. Our final dataset consists of 16,011 unique locations belonging to 93 companies, with a total number of 19,343 location-time observations.

2.3.2 Variables

Dependent variables

Radicalness. To measure the radicalness of a patent family, we adopt the radicalness index proposed by Funk and Owen-Smith (2017), which captures the degree to which the focal patent destabilizes existing technology trajectories. Funk and Owen-Smith's measure is a second-order view of the impact that captures the extent to which subsequent inventions build on a technology also rely on that technology's prior arts. More specifically, the radicalness index examines whether patents citing a focal patent also cite prior patent cited by the focal patent (i.e., its references). If patents citing the focal patent do not cite its references, then the focal patent is considered to reshape the network of technology interlinkages by shifting future inventors' attention away from the knowledge on which the focal patent builds, thus destabilizing existing technology trajectories. This measure makes it possible to distinguish between destabilizing and consolidating technologies that may have similar impact but very different consequences for existing trajectory. Employing the measure developed by Funk and Owen-Smith (2017), Wu et al. (2019) studied the relationship between team size and destabilizing/consolidating tendency of team product using data about patents, scientific papers, and software products. They found that small teams are inclined to destabilize science and technology, whereas large teams are more likely to consolidate existing ones. Balachandran and Hernandez (2018) divided firms' networks into foreign, domestic, and mixed triads according to whether the broker and its partners across institutional boundaries and investigated how institutions and networks jointly influence innovation. The result showed that foreign triads have a greater influence on radical innovation. Park et al. (2023) applied this measure to papers and patents and found that they are becoming less radical over time. Several studies have proposed similar measures as Funk and Owen-Smith's measure, following a network approach (Bu et al., 2021; Chen et al., 2021; Shibayama & Wang, 2020). Hence, previous research suggests that the radicalness index developed by Funk and Owen-Smith (2017) can serve as a useful measure of the radicalness of a patent. In this study, we follow Funk and Owen-Smith's (2017) approach, *radicalness* is calculated as follows for a focal patent:

$$\text{Radicalness} = \frac{1}{n}\sum_{i=1}^{n} f_i$$

Where i is the index of the future patent families that cite the focal patent family or its references, n is the total number of such future patent families. f_i equals 1 if the future patent family i only cites the focal patent family but not any references of the focal patent family, f_i equals -1 if the future patent family i cites not only the focal patent family but also at least one of its references, and f_i equals 0 if the future patent family i only cites the focal patent family' references but not the focal patent family. Hence, radicalness indicates the extent to which the focal patent family obsoletes prior arts that it builds on in a dynamic network. The range of radicalness index is from -1 to 1. For calculating radicalness, we adopt a fixed 5-year citation time window, that is, future citing patent families which have an earliest filing date within 5 years after the focal patent family are considered. This allows patent families filed in different years to have the same number of years for accumulating citations. Results are robust when we consider all future patents without the fixed time window.

At the location level, we calculate the average radicalness in a 3-year moving time window to characterize the inclination towards radical innovation for the location in this time period.

Independent variables

Tie strength. Many studies focus on the frequency of interactions as the most important property and use it to capture the essence of what Granovetter was referring to when he spoke of the strength of a tie (Fleming et al., 2007; Granovetter, 1973; Wang, 2016). In this paper, we follow this common approach and measure tie strength between two R&D locations as their frequency of co-inventing patent families. We only consider direct ties but not indirect ties, because direct ties play a more direct and critical role in knowledge creation and transfer (McFadyen & Cannella Jr, 2004), which allow us to investigate the effect of collaboration networks on innovation radicalness. We also need to convert tie strength from the dyadic level to the network level. Following previous research, average network tie strength is used to indicate the overall tie strength in a focal location's egocentric network (Wang, 2016). In this way, tie strength at the network level is a simple aggregation of ties at the dyadic level. In this study, we operationalized tie strength (*tie strength*) as the number of co-inventing patent families in a 3-year moving time window. Specifically, we first count the number of co-inventing patent families between a focal location and its collaborating locations. Then we calculate the tie strength as the average tie strength.

Structural hole. Several different formulas for structural hole have been proposed and used in the literature (Borgatti, 1997; Burt, 1992; Rodan, 2010). Among them the density of a location's egocentric network provides an intuitive indication of the absence of structural holes in the network. This simple formulation also has an advantage that it does not make assumptions about the behavior of actors in the network, while Burt's original indicator relies some assumptions about the behavior of nodes and tie formulation (Burt, 1992; Rodan, 2010). We follow this approach and first calculate the density of an egocentric network, as the number of existing ties between alters divided by the number of all possible alter-alter ties. Same as for measuring tie strength, we use co-inventing as a tie, and use a 3-year moving time window for identifying alters and ties. As network density is the opposite to structural hole, we calculate structural hole as 1-density, in other words, the share of missing ties in an egocentric network excluding the ego itself. The range of structural hole is from 0 to 1. A higher value indicates a higher level of richness in structural holes.

Control variables

Our analyses control for possible confounding variables that may lead to spurious correlations between our focal independent and dependent variables. We use fixed effects models incorporating firm-location fixed effects, so that we can account for unobservable time-invariant location heterogeneity and test for variations within firm-location. *Innovation productivity*, measured as the number of patent families, is included, considering that a more productive location might also have a higher chance of forming certain types of networks and at the same having a higher chance of producing radical innovation (Fleming et al., 2007). To examine the effect of network properties net of network size, we control for *network size*, which is the number of co-inventing locations. Controlling for the number of co-inventing locations can help to exclude the possible alternative explanation that it was the network size that predicted variation in network properties and radicalness. To account for the general inclination towards collaborating, we also included the share of a location's patent families that are co-invented with other locations (*collaboration inclination*). For *innovation productivity*, *network size*, and *collaboration inclination*, we also use a 3-year moving time window for constructing these variables. Time (i.e., one time period is three years) dummies are also included to control for general time differences applying to all sampled firm-locations.

2.4 Result

2.4.1 Descriptive statistics

Table 2.1 reports descriptive statistics and spearman correlations for our variables in the panel dataset. *Radicalness* has a mean of -0.01, standard deviation of 0.06, and ranges from -0.47 to 0.90. The slightly right-skewed distribution indicates that in general consolidating, incremental innovations are more common than radical innovations, as expected. The distribution of *tie strength* is highly right-skewed with a mean of 1.86 and standard deviation of 2.16, and ranging from 1 to 69.60. We take the natural logarithmic transformation for *tie strength*, as well as all other count variables (i.e., *innovation productivity* and *network size*) to accommodate the skewed nature of these variables. *Structural hole* has mean 0.80 and ranges from 0 to 1. This suggest that most locations operate in relatively sparse networks that are rich in structural holes. Moreover, there is considerable heterogeneity among locations. On average, the number of patent families (i.e., *innovation productivity*) is 6.72, the number of co-inventing locations (i.e., *network size*) is 7.91, and 97% patents involves collaboration with other locations (i.e., *collaboration inclination*), indicating that sole-production of innovation is rare. Correlations show that both tie strength (r=-0.04) and structural hole (r=-0.02) are negatively correlated with radicalness. It is important to interpret these correlations with caution as they do not account for any confounding variables. The correlations between our focal independent variables and control variables (especially innovation productivity) are fairly high: innovation productivity has a correlation of 0.86 with tie strength and -.79 with structural hole. While for the reasons discussed in the section on control variables, we report results with controlling these potential confounders in this paper and test the robustness of our results without controlling one of any of these controls.

Table 2.1: Descriptive statistics and correlations (*N*=19,343)

	Variable	Mean	S.D.	Min	Max	1	2	3	4	5
1	Radicalness	-0.01	0.06	-0.47	0.90					
2	Tie strength	1.86	2.16	1	69.60	**-0.04**				
3	Structural hole	0.80	0.28	0	1	**-0.02**	**-0.48**			
4	Innovation productivity	6.72	19.61	1	466	-0.01	**0.86**	**-0.79**		
5	Network size	7.91	9.58	2	122	**-0.09**	**0.46**	**-0.65**	**0.62**	
6	Collaboration inclination	0.97	0.11	0.07	1	**-0.04**	**-0.26**	**0.42**	**-0.49**	**-0.27**

Note: Correlation with bold numbers significant at $p < .05$

2.4.2 Regression results

To explore the relationship between network structure and innovation radicalness, we performed fixed-effects linear regressions, using *radicalness* as the dependent variable. For all regression models, we incorporate firm-location fixed effects and estimates within-firm-location effects. We also control for the set of control variables as discussed in the previous section.

Table 2.2 reports results of fixed effects linear models. Column 1 is a baseline model which only include control variables. We found that *innovation productivity*, i.e., the number of patent families, has a significantly positive effect on *radicalness*, suggesting that a location is more likely to produce radical innovation when it is more productive. *Network size*, i.e., the number of co-inventing locations, has a negative effect on radicalness, suggesting that when a location holds a more central location within a company's internal network, it is less likely to produce radical innovation. Similarly, *collaboration inclination*, i.e., share of patent families that are co-inventions with other locations, also has a negative effect. These observations are consistent with the expectation that radical innovation is more likely to come from the peripheral and isolated places in the network (Cattani & Ferriani, 2008).

Table 2.2: Fixed effects linear models: Network structure and innovation radicalness

	Radicalness			
	(1)	(2)	(3)	(4)
Tie strength (ln)		-0.013***	-0.011***	-0.016***
		(0.002)	(0.002)	(0.003)
Structural hole			-0.005	-0.007*
			(0.004)	(0.004)
Tie strength (ln) * Structural hole				0.007**
				(0.003)
Innovation productivity (ln)	0.004***	0.013***	0.011***	0.011***
	(0.001)	(0.002)	(0.002)	(0.002)
Network size (ln)	-0.006***	-0.010***	-0.010***	-0.010***
	(0.001)	(0.002)	(0.002)	(0.002)
Collaboration inclination	-0.014***	0.001	-0.002	-0.001
	(0.005)	(0.005)	(0.006)	(0.006)
Year FE	Yes	Yes	Yes	Yes
Firm-location FE	Yes	Yes	Yes	Yes
N	19343	19343	19343	19343
R-square	0.696	0.697	0.697	0.698

Note: Robust standard error in parentheses. ***p < 0.01; **p < 0.05; *p < 0.1.

Column 2 adds tie strength into the regression model. *Tie strength* has a significantly negative effect on *radicalness*. Thus, hypothesis 1 is supported, which is about the informational advantages of weak ties. Within the same firm-location, holding all other variables constant, the expected degree of radicalness decreases as average tie strength of the egocentric network increases.

Column 3 further adds structural holes into the regression model. While the negative effect of tie strength remains significant, *structural hole* does not have a significant effect on *radicalness*, which does not support hypothesis 2 which states a positive effect of structural hole on innovation radicalness.

Column 4 further adds the interaction term between *tie strength* and *structural hole* into the regression. We observe a significantly positive interaction effect. This result supports hypothesis 3. More specifically, structural holes weaken the negative effect of tie strength, and tie strength magnifies the positive effect of structure holes. Note that when the interaction term between *tie strength* and *structural hole* is added, the coefficient of *tie strength (ln)* (i.e., -0.016) indicates the marginal effect of *tie* *strength (ln)* on *radicalness* when *structural hole* equals 0, which is the minimum value of *structural hole* (theoretically and empirically in our sample). Similarly, the coefficient of *structural hole* (i.e., -0.007) indicates the marginal effect of *structural hole* on *radicalness* when *tie strength (ln)* equals to 0, which is also the minimum value of *tie strength (ln)*. To facilitate the interpretation of the interaction effect, Figure 2.1A plots the marginal effects (i.e., regression coefficients) of *tie strength (ln)* at different levels of *structural hole*. It shows that when *structural hole* is relatively low, *tie strength* has a significantly negative effect, but as structural hole increases, this negative effect shrinks in size. This is in line with the argument that when a network is dense (structural hole is low), the informational advantages of weak ties (i.e., negative effects of tie strength) can be mobilized and translate into innovation advantages. On the other hand, when the network is rich in structural holes, the informational advantage of weak ties cannot be effectively mobilized, so that the negative effect of tie strength becomes smaller. Similarly, Figure 2.1B plots the marginal effects (i.e., regression coefficients) of *structural hole* at different levels of *tie strength*. It shows that when tie strength is relatively low, structural hole has a negative effect. However, as tie strength increases, the effect of structural hole increases and becomes significantly positive. This finding is also in line with the argument that, having strong ties is necessary for mobilizing informational advantages of structural holes for developing radical innovation.

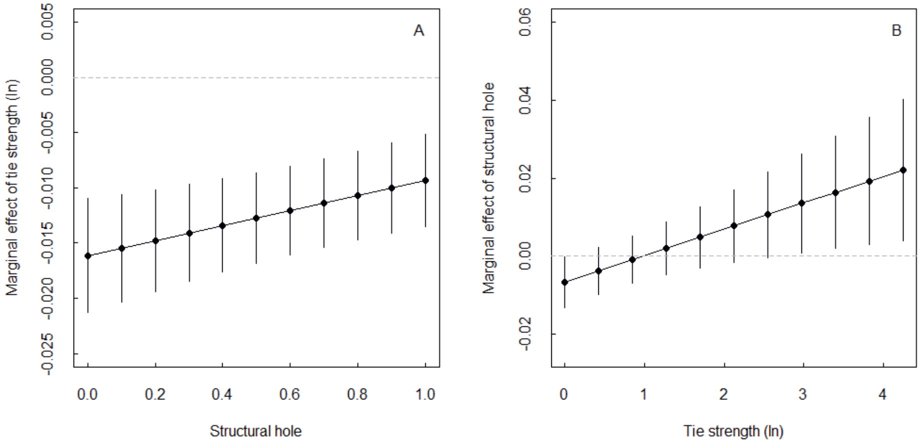

Figure 2.1: Tie strength, structural hole, and innovation radicalness. Points represent the regression coefficients, and vertical bars represent 90% confidence interval.

2.4.3 Robustness tests

For calculating radicalness, we adopt a fixed 5-year citation time window, that is, future citing patent families which have an earliest filing date within 5 years after the focal patent family are considered. This allows patent families filed in different years to have the same number of years for accumulating citations. Results are robust when we consider all future patents up to 2019 (i.e., in PATSTAT 2019 Autumn version) without the fixed time window (Appendix Table A1).

Our regression analysis included innovation productivity, network size, and collaboration inclination as control variables, for the reasons discussed in the control variable section. However, there are relatively high correlations between our focal independent variables and these control variables, raising concerns of multilinearity. We test whether our results are sensitive to having these control variables. We tried to drop each of them as well as dropping them all together. Results are robust (Appendix Table A2).

2.5 Conclusion

In this study, we investigated the relationship between network structure and radical innovation in the context of corporate R&D networks. In terms of the network structure, we focused on the strength of ties and structural holes. We build a unique panel dataset consisting of 19,343 firm-location-time observations for 16,011 unique firm-locations belonging to 93 U.S. pharmaceuticals and biotechnology companies on the EU Industrial R&D Investment Scoreboard. We fitted fixed effects linear models to investigate within-firm-location effects. On the one hand, we found a significant negative effect of tie strength on innovation radicalness, confirming the informational advantages of weak ties for radical innovations. On the other hand, we do not observe a significant effect of structural hole. More importantly, we observe a significantly positive interaction effect between tie strength and structural hole on innovation radicalness. More specifically, the negative effect of tie strength is weaker when the network is rich in structural holes, and the effect of structural hole is negative when tie strength is weak but positive when tie strength is strong. This suggest that network cohesion is required for mobilizing the informational advantages of weak ties for radical innovation. Similarly, strong ties are needed for mobilizing the informational advantages of structural holes.

This study has several limitations. First, patent data provide a useful data source for mapping collaboration networks and characterizing innovation radicalness, with the added advantage of avoiding the nonresponse biases that characterize surveys and interviews. However, it also has some disadvantages, which we cannot avoid. Many unimportant inventions fail to be patented, and some breakthroughs may be missed for strategic reasons (Fleming, 2001). While granted patents are not a perfect archive of technological innovations, the data still represent a considerable share of invention outputs with varying degrees of radicalness. Future research adopting a broader set of innovation outputs would be valuable to expand beyond patents to other innovative outputs. Second, patent data do not provide direct information for measuring the underlying mechanisms posited by our hypotheses. Our theory separates two faces of weak ties and structural holes: their informational advantages and relational disadvantages, which however cannot be measured using patent data. Future research should address this issue and explore alternative data sources for a more direct test of the theory. Third, like most network studies, this study focuses on the structural aspect of the network but does not account for the characteristics of nodes or the content of things that are exchanged in the context of the tie. Future research should incorporate these aspects for a better and more complete understanding of the relationship between collaboration networks and radical innovation. Fourth, this study focused on the pharmaceutical and biotechnology industry, which may limit the generalizability of our findings to other industries. It is worthwhile for future research to investigate field contingence effects.

This paper makes theoretical contributions to several areas of research. First, it contributes to the social network literature, by proposing a two-faced view of network structures separating informational and relational aspects, and investigating the interaction between different network properties. This provides a promising direction for reconciling competing theories about network effects (Burt, 1992; Coleman, 1988; Granovetter, 1982; Granovetter, 1973; Uzzi, 1996, 1997). Our conceptual model and empirical findings acknowledge that the same network structure (i.e., weak tie, structural hole) may present both informational advantages and relational disadvantages at the same time. In addition, the informational advantages of weak ties can be mobilized if there are network cohesion to mitigate the relational disadvantages of weak ties. Similarly, the informational advantages of structural hole can be mobilized if there are strong ties to mitigate the relational advantages of structural holes. Second, this study contributes to the radical innovation literature. Prior studies have extensively investigated the technological origin and economic consequences of radical innovation. This study explored the social determinants of radical innovation in the organizational and social environment. In particular, characteristic of collaboration networks. Third, this study contributes to the R&D location decisions literature, while prior studies have long investigated factor driving multinationals' overseas R&D location choices and strategies for coordinating subsidiaries (Alcácer & Zhao, 2012; Belderbos et al., 2021; Du et al., 2022; Kuemmerle, 1997; Lewin et al., 2009), this study explores how the structure of firm R&D networks affects its ability of producing radical innovation.

Our study also has important implications for innovating companies aspiring to develop radical innovation. Our findings suggest that having weak ties are generally more conducive for radical innovation, but it is especially beneficial when weak ties are accompanies by network cohesion. On the other hand, structural holes are beneficial for developing radical innovation if there are strong ties to mitigate its relational disadvantages.