The Impact of Small-World Characteristics of Patent Collaboration Networks on Firm Technological Innovation Performance (Postprint)

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Date: 2023-04-01T00:00:00+00:00

Abstract

[Purpose/Significance] This study analyzes the impact of firms' egocentric network characteristics on their technological innovation performance under the moderation of small-world properties in patent cooperation networks, providing a foundation for firm technological innovation management.

[Method/Process] Patent cooperation networks are constructed based on copatentee relationships among firms. The number of patents applied for and granted by firms serves as the measure of technological innovation performance. Egocentric network size, egocentric network density, and firm collaboration partners are employed as independent variables, while small-world characteristics of patent cooperation networks serve as the moderating variable to construct a theoretical model of firm technological innovation performance. An empirical analysis is conducted using firms in the speech recognition technology sector as the research sample.

[Results/Conclusion] The empirical analysis reveals the influence of firms' egocentric network characteristics on technological innovation performance and clarifies the mechanism through which small-world characteristics of patent cooperation networks affect firm technological innovation performance. The results demonstrate that small-world networks strengthen the effect of egocentric network density on firm innovation performance via their high clustering coefficient. Based on these findings, countermeasures and recommendations for enhancing firm technological innovation performance are proposed.

Full Text

Research on the Impact of Small-World Characteristics of Patent Cooperation Networks on Enterprise Technological Innovation Performance

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Abstract: [Purpose/Significance] This study analyzes the impact of enterprise ego-network characteristics on technological innovation performance under the moderating effect of small-world characteristics in patent cooperation networks, providing a basis for enterprise technological innovation management. [Method/Process] The study constructs patent cooperation networks based on co-patentee relationships between enterprises, measures enterprise technological innovation performance by the number of patents applied for and granted, and builds a theoretical model with enterprise ego-network scale, ego-network density, and cooperation partners as independent variables and patent cooperation network small-world characteristics as a moderating variable. An empirical analysis is conducted using enterprises in the speech recognition technology field as research samples. [Result/Conclusion] The empirical analysis reveals the impact of enterprise ego-network characteristics on technological innovation performance and clarifies the mechanism through which patent cooperation network small-world characteristics influence enterprise innovation performance. The results show that small-world networks enhance the impact of enterprise ego-network density on innovation performance through their high clustering coefficient. Based on these findings, countermeasures and suggestions for improving enterprise technological innovation performance are proposed.

Keywords: patent; cooperation network; ego-network; small-world; technological innovation performance
Classification Number: C93
DOI: 10.13266/j.issn.0252-3116.2021.18.011

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2 Related Research

Theoretically, small-world networks provide possibilities for knowledge dissemination, but interaction management and participant behavior may complicate the simple relationship between small-world characteristics and innovation. After successfully demonstrating the existence of small-world networks, scholars began exploring the impact of small-world network structural features on organizations, industries, and broader economic functions. Current research on the impact of patent cooperation network small-world characteristics on innovation performance is primarily conducted at macro, meso, and micro levels.

At the macro level, research focuses on how small-world characteristics of international patent cooperation networks affect national innovation performance. Empirical studies have found that small-world networks of knowledge diffusion between countries reduce developmental imbalances, that international patent cooperation significantly promotes both innovation quantity and quality, and that there is a negative correlation between network average path length and innovation performance, while an inverse U-shaped relationship exists between network small-world characteristics and innovation performance. China's patent cooperation networks exhibit more pronounced small-world characteristics, but their impact on innovation performance is only significant in certain regions, as the existence of numerous state-owned enterprises lengthens small-world paths and thereby affects knowledge transmission efficiency.

At the meso level, research examines how inter-regional patent cooperation networks affect regional innovation performance. L. Fleming and A. L. Juda et al. found that the high clustering characteristic of small-world networks has no significant relationship with regional innovation performance, but shorter average paths and larger network components positively influence regional innovation performance. Zhao Liangjie and Song Bo discovered that network small-world characteristics have a negative impact on the short-term innovation performance of technological innovation alliance networks but a positive impact on long-term performance. Wu Hui and Gu Xiaomin found that small-world characteristics of Shanghai's pharmaceutical industry cooperative innovation network negatively affect cluster innovation performance.

At the micro level, research investigates how inter-firm patent cooperation networks affect innovation performance. It is now widely accepted that the impact of high clustering and short path length on enterprise innovation performance is inverted U-shaped. B. Uzzi and J. Spiro predicted an inverted U-shaped relationship between the clustering and small-world characteristics of cooperation networks and the performance of Broadway creative artists, while path length was negatively correlated with artistic performance. Y. Shi et al.'s study of China's nanotechnology field patent cooperation networks found that path length has no significant impact on individual innovation performance, network clustering coefficient has no significant impact on individual innovation performance, and small-world characteristics have an inverted U-shaped relationship with innovation performance, with this inverted U-shaped threshold being significantly smaller at the network level.

Although some research has been conducted at the enterprise level on patent cooperation networks, these studies have not adequately distinguished between different types and characteristics of cooperation centered on enterprises, neglecting the impact of network heterogeneity and enterprise agency on cooperation networks. Essentially, in patent cooperation networks, enterprises primarily achieve structural and functional effects of cooperation networks by attracting other enterprises and establishing cooperative relationships, thereby obtaining more knowledge, technology, and social resources that influence their technological innovation performance. Ego-network scale and density effectively measure this influence mechanism, while the type of cooperation partners enterprises choose also significantly impacts their ability to maintain competitive advantages and supplement innovation knowledge and technology.

In summary, the impact of small-world characteristics on innovation performance remains controversial, with inconsistent research findings across national, regional, and industry levels. Current research has several limitations: (1) Many studies on patent cooperation networks remain at the level of analyzing network structural attributes and their evolution, revealing small-world and scale-free characteristics but lacking research on how network structural attributes affect individuals; (2) Current research emphasizes national and regional levels, with less focus on enterprise and inventor individual levels, possibly due to difficulties in processing enterprise-level and individual-level data and complexity in calculating network structural characteristics; (3) Due to the typical characteristics of high clustering and short path length in small-world networks, it is generally believed that small-world characteristics significantly enhance enterprise technological innovation performance, but the influence mechanism remains unclear; (4) Most current research treats patent cooperation network small-world characteristics as independent variables analyzing their impact on enterprise technological innovation performance, when in fact small-world characteristics are overall network attributes while enterprises are individuals within the network, and network-level attributes often affect individuals indirectly through moderating effects that alter individual ego-networks.

Based on the above analysis, this paper combines empirical analysis in the speech recognition technology field to measure inter-firm patent cooperation network structural attributes and enterprise ego-network structural attributes, analyzing the mechanism through which patent cooperation network small-world characteristics, as a moderating variable, affect enterprise technological innovation performance, to provide decision-making basis for enterprise technological innovation management.

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3 Theoretical Analysis and Research Hypotheses

According to social network theory, social networks are primarily analyzed through two frameworks: whole networks and ego-networks. The former reflects overall network structural characteristics, while the latter reflects the social relationship structure maintained by individuals. An enterprise's ego-network in patent cooperation networks can be viewed as an important way for enterprises to utilize social networks for technological innovation, and the influence mechanism of ego-network structural attributes on enterprise technological innovation performance warrants in-depth research. An ego-network is defined relative to a whole network: for a given person (denoted as A), considering only this person and his/her friends, as well as the connections between these friends, yields A's ego-network.

3.1 Enterprise Ego-Network Scale and Technological Innovation Performance

Enterprise ego-network scale refers to the number of nodes directly connected to the enterprise. Social capital theory posits that social capital, in addition to economic and human capital, is an important factor determining individual success. Social capital refers to the disposable resources individuals have in social networks, primarily including information resources and individual agency or influence. From a social capital perspective, a larger ego-network scale means more social relationship resources for the node, richer heterogeneous information obtained, and thus greater benefits for knowledge innovation activities. From an information dissemination perspective, a larger ego-network scale means faster and broader information transmission, more easily forming an upward spiral of knowledge flow, thereby benefiting knowledge innovation activities. As market competition environments become increasingly complex, enterprises continuously seek quality cooperation partners to gain technological advantages. Through industry-university-research cooperation with universities and research institutes, enterprises can not only reduce technological innovation costs and disperse innovation risks but also obtain innovative ideas and knowledge from these institutions through knowledge spillover effects, thereby promoting technological innovation performance. Therefore, this paper proposes:

Hypothesis 1: Enterprise ego-network scale has a positive impact on technological innovation performance.

3.2 Enterprise Ego-Network Density and Technological Innovation Performance

Network density is an important structural feature of ego-networks, measuring the closeness of connections between nodes in the network. Greater density indicates closer relationships among nodes. Generally, higher network density means greater social cohesion among network members and smoother information transmission and sharing. From a social capital perspective, however, higher density is not always better in inter-firm patent cooperation networks. Both maintaining existing social relationships and developing new ones require time and resource costs. If enterprises cannot effectively handle the balance of multiple networks, they risk becoming over-embedded in social networks. Over-embedding turns social capital into a social burden. When leveraging social networks to obtain social capital, enterprises must maintain moderate network embeddedness, focusing limited time and energy on identifying higher-quality resources and avoiding excessive trust and dependence on existing social relationships. As R. S. Burt's structural holes theory suggests, excessive network density can easily lead to redundancy of information and knowledge within the network, thereby reducing knowledge flow efficiency—a situation particularly prominent in ego-networks. On one hand, the possibility of information homogeneity increases; on the other hand, close-knit cooperation teams exclude external information, further reducing connections between the central enterprise and external innovation actors. Simultaneously, for enterprises, maintaining close cooperation teams further increases technological innovation costs. Based on the above analysis, this paper proposes:

Hypothesis 2: Enterprise ego-network density has a negative impact on technological innovation performance.

3.3 Enterprise Cooperation Partners and Technological Innovation Performance

Existing research shows that partner types affect patent output. There is an inverted U-shaped relationship between partner technological similarity and patent performance, meaning that a certain cognitive distance between partners benefits technological innovation. Therefore, large companies may tend to cooperate with younger companies to create patents, supplementing technological reserves through specific project cooperation. Repeated cooperation negatively impacts patent output. Thus, in patent cooperation, partner types and cooperation forms affect enterprise innovation performance. Meanwhile, large companies face a dilemma when pursuing cooperative competition with competitors: attractive opportunities coexist with the risk of being appropriated by partners. Based on the above analysis, this paper argues that large companies choosing small companies as cooperation partners is more conducive to technological innovation performance, as it can both reduce cooperative competition risks and supplement technological and knowledge storage for specific projects.

Therefore, this paper proposes:

Hypothesis 3: The proportion of small companies among enterprise cooperation partners has a positive impact on technological innovation performance.

The speech recognition technology field is a knowledge-intensive industry with diverse cooperation partners, including universities, research institutes, large companies, startups, and small companies. Limited by sample data, this paper focuses on analyzing the impact of two types of cooperation partners—standard companies and non-standard companies—on enterprise innovation performance. According to the Derwent Patent Database, standard companies are those with over 1,000 patent outputs, which this paper defines as large companies, while non-standard companies with fewer patent outputs are defined as small companies.

3.4 The Moderating Effect of Small-World Characteristics on Ego-Network and Innovation Performance

Small-world networks are network models that, compared to random networks of the same size, have larger clustering coefficients and shorter average shortest path lengths. Small-world characteristics have been widely confirmed as typical features of patent cooperation networks and significantly impact innovation performance. L. Fleming et al.'s empirical research shows that patent cooperation network clustering coefficients, average shortest path lengths, and their interaction significantly impact innovation performance. B. Uzzi and J. Spiro used the ratio of the two to obtain the small-world characteristic value SW and analyzed its impact on innovation performance. Most current research treats whole cooperation network small-world characteristics as independent variables, but small-world characteristics are variables at the whole network level, while enterprise ego-network characteristics and technological innovation performance are individual-level variables, creating structural differences. Therefore, this paper argues that whole cooperation network small-world characteristics do not directly affect individual innovation but indirectly affect individual innovation performance by acting on individual ego-networks. Thus, unlike previous research that treats small-world characteristics as independent variables, this paper treats small-world characteristics as a moderating variable to analyze its moderating effect on ego-network and enterprise technological innovation performance, enhancing or weakening the impact of enterprise ego-network scale and density on innovation performance, and deeply analyzing the influence mechanism of small-world characteristics on enterprise technological innovation performance.

Research has found that in dynamic systems with small-world characteristics, information dissemination and computational capabilities are enhanced. Information dissemination has a social reinforcement effect. When the whole patent cooperation network has a high clustering coefficient, indicating active local exchanges and interactions, information dissemination is strengthened locally, which benefits the expansion of enterprise ego-network scale. When the whole patent cooperation network has a short average path length, information spreads faster, helping enterprises find more suitable cooperation partners and also benefiting ego-network scale expansion. Based on the above analysis, this paper proposes:

Hypothesis 4a: Small-world characteristics have a positive moderating effect on the relationship between ego-network scale and technological innovation performance.

Some evidence suggests that the relationship between small-world characteristics and innovation may actually be curvilinear, as some small-world characteristics enhance information flow, but excessive small-world characteristics create information redundancy and reduce novelty. When the whole network clustering coefficient reaches a certain level, further increases significantly raise enterprise ego-network density, making connections between partners closer. Based on the above analysis, this paper proposes:

Hypothesis 4b: Small-world characteristics have a positive moderating effect on the relationship between ego-network density and technological innovation performance.

Based on the above theoretical analysis, this paper proposes a theoretical model of the impact of enterprise ego-network characteristics and small-world characteristics on technological innovation performance, as shown in Figure 1 [Figure 1: see original paper].

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4 Research Design

4.1 Research Sample

The research sample consists of enterprises in the speech recognition technology field, with patent data sourced from the Derwent Patent Database. This paper selects the speech recognition technology field primarily because speech recognition is a key application area of artificial intelligence with rapid technological updates, allowing observation of significant evolutionary characteristics in patent cooperation network structure and enterprise ego-networks, which is highly beneficial for analyzing the impact of patent cooperation network small-world characteristics on enterprise technological innovation performance. Speech recognition technology primarily involves technical fields such as speech analysis or synthesis, speech recognition, speech or sound processing, and speech or audio encoding or decoding, with International Patent Classification (IPC) subclass G10L. The Derwent Patent Database assigns 4-letter unique institutional codes (ABCD-C) to large companies with over 1,000 patents, called standard companies, while other non-standard companies use codes ABCD-N and ABCD-R (Russia). Non-standard companies can be identified based on country, region, city, and company address information. Because institutional codes are unique, this paper sets research subjects as standard companies. Through IPC retrieval, 165 standard companies participating in patent cooperation were obtained, ultimately yielding 1,005 unbalanced panel sample data points from 1990-2014, with retrieval conducted in April 2019.

4.2 Network Construction

Inter-firm cooperative relationships generally last 3-5 years. This paper uses a 5-year moving window to divide enterprise patent cooperative relationships from 1990-2014 into 21 stages (1990-1994, 1991-1995, …, 2010-2014). In each stage, patent cooperation networks are constructed based on co-patentee relationships between enterprises. Taking the 1990-1994 stage as an example: standard and non-standard companies are identified by patentee 4-letter institutional code information, with standard companies as research samples and non-standard companies identified by address not included as research samples but participating in network construction; all patents are traversed based on co-patentee relationships to obtain network edges and their weights, thereby generating the cooperation network.

4.3 Network Indicator Calculation and Variable Measurement

4.3.1 Whole Cooperation Network Indicators Whole cooperation network indicators involve whole network density, average clustering coefficient, average shortest path length, small-world characteristic value, betweenness centrality, etc., with specific calculation methods shown in Table 1 .

4.3.2 Ego-Network Indicators Enterprise ego-network characteristic indicators involve ego-network scale, network density, and enterprise cooperation partners, with specific calculation methods shown in Table 1.

4.3.3 Variable Measurement The dependent variable is enterprise technological innovation performance, independent variables are enterprise ego-network characteristics, the moderating variable is whole cooperation network small-world characteristics, and control variables are enterprise technological innovation accumulation, whole network density, and enterprise betweenness centrality in the whole network. Specific variable descriptions and calculation methods are shown in Table 1, with explanations for some variables as follows:

(1) **Technological Innovation Performance:** Measured by the number of patents applied for and granted annually by enterprises. Considering the lag effect of patent cooperation network structure on enterprise technological innovation performance, patent counts with 1-year, 2-year, and 3-year lags are used as dependent variables, denoted as Patents_i,t+1, Patents_i,t+2, Patents_i,t+3.

(2) **Enterprise Cooperation Partners:** This variable measures the proportion of small companies (i.e., non-standard companies) among enterprise cooperation partners.

(3) **Enterprise Technological Innovation Accumulation:** To control for unobserved heterogeneity in enterprise patent behavior (e.g., differences in R&D expenditure, patent propensity, or capabilities), this paper follows R. Blundell et al.'s method, defining enterprise technological innovation accumulation as the total number of patents obtained by the company in the three years before entering the sample. This indicator effectively measures the accumulation of prior technological innovation.

(4) **Betweenness Centrality:** Research shows that companies occupying more central positions in cooperation networks tend to generate more innovation than peripheral companies. Node betweenness centrality indicates a node's ability to access different information flows and act as a

gatekeeper or intermediary. This paper uses normalized betweenness centrality to make the measure comparable across time and different stages of the network.

(5) **Whole Network Density:** When whole network density captures the global density (or sparsity) of the entire network, the clustering coefficient captures the degree to which the entire network has locally dense regions. A network can be globally sparse yet still have a high clustering coefficient because the speed and extent of information diffusion in the whole network increase with density, thereby facilitating enterprise absorption and utilization of new knowledge and technologies and benefiting technological innovation. Therefore, this paper includes whole network density as a control variable.

4.4 Statistical Model Construction

Patent output is a typical non-negative count variable. Additionally, since the variance of cooperative patent counts among speech recognition technology enterprises is greater than the mean, exhibiting overdispersion (see Table 2), following existing research, patent output is assumed to follow a negative binomial distribution, and a negative binomial regression model is applied for empirical research. Using the Hausman test at a significance level of $p<0.0001$, the random effects model is rejected, so a fixed-effects negative binomial model is used. Fixed-effects negative binomial regression helps control for unpredictable, time-invariant influencing factors. The model expression is:

Patents_i,t+y = f(Cooperator_i,t, PL_{ratio}t, CC_{ratio}t, SW_t, Ego_{size}i,t × PL_{ratio}t, Pre-sample_{Patents}i,t, BC_i,t, Who_{density}t, Ego_{size}i,t, Ego_{density}i,t, Ego_{size}i,t × CC_{ratio}t, Ego_{size}i,t × SW_t, Ego_{density}i,t × PL_{ratio}t, Ego_{density}i,t × CC_{ratio}t, Ego_{density}i,t × SW)

where i represents enterprises, t represents network division stages, and y=1,2,3 represents 1-year, 2-year, and 3-year time lags, respectively.

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5 Empirical Results and Analysis

5.1 Sample Patent Cooperation Network Structure Analysis

This paper uses the Python-based NetworkX complex network analysis toolkit to construct and analyze patent cooperation networks. Table 3 describes the number of nodes, number of edges, network density, average clustering coefficient, average shortest path length, and the average clustering coefficient and average shortest path length of random networks of the same size for each stage, calculating CC_{ratio} and PL_{ratio}, and finally calculating the small-world characteristic value SW for each stage's patent cooperation network. Table 3 shows that the small-world characteristic values SW for all stages are large, with an average of 159.3257, far exceeding the network small-world characteristic values in literature, indicating that enterprise patent cooperation networks in the speech recognition technology field have typical small-world characteristics.

5.2 Sample Descriptive Statistical Analysis and Correlation Analysis

This study uses R software for descriptive statistics and variable correlation analysis of sample data, along with collinearity analysis (see Tables 2 and 4). Table 2 shows that the mean and variance of dependent variables differ greatly, making negative binomial regression modeling appropriate. Experience indicates that when VIF >= 10, serious multicollinearity exists among independent variables. Table 4 shows that the VIF values between CC_{ratio} and SW variables are high, with correlation coefficients greater than 0.7, indicating substantial collinearity. However, SW and CC_{ratio} are not placed in the same regression equation in the statistical model, so their collinearity issue does not affect the regression model. Except for SW and CC_{ratio}, VIF values among other variables are all less than 5, indicating that overall, the statistical model has no collinearity problems.

5.3 Negative Binomial Regression Analysis

The negative binomial regression results for statistical data are shown in Table 5 . Model 1 is the baseline model containing only control variables. The results show that enterprise technological innovation accumulation, whole network density, and enterprise betweenness centrality in the whole network all have significant positive impacts on innovation performance, consistent with existing research. However, from Models 2 to 8, after adding other variables, the positive impact of betweenness centrality on innovation performance is not always significant, indicating that its impact is susceptible to interference from other variables.

Models 2-4 show regression results after adding the three independent variables: enterprise ego-network scale, enterprise ego-network density, and enterprise cooperation partners. The results indicate that enterprise ego-network scale has a significant positive impact on technological innovation performance, verifying Hypothesis 1 and aligning with previous research, showing that expanding cooperation scale benefits enterprise technological innovation performance. Enterprise ego-network density has a significant negative impact on innovation performance; when the core network centered on the enterprise is too close, redundant information increases, and maintaining such strong cooperative relationships becomes burdensome, consistent with theoretical analysis and verifying Hypothesis 2. The enterprise cooperation partners variable, measuring the proportion of cooperation with small companies, has a significant positive impact on innovation performance, verifying Hypothesis 3. Cooperation between large and small companies can effectively reduce cooperative competition risks while supplementing technological and knowledge storage through targeted project cooperation, thus better promoting technological innovation performance.

Model 5 adds the moderating variable small-world characteristic value SW based on Model 2. The regression results show that the interaction term coefficient between enterprise ego-network scale and SW is not significant, meaning small-world characteristics have no significant effect on the positive impact of ego-network scale on innovation performance, and Hypothesis 4a is not supported.

Models 6, 7, and 8 add three moderating variables—small-world characteristic value SW, network average clustering coefficient ratio CC_{ratio}, and network average shortest path length ratio PL_{ratio}—based on Model 3. Model 6 results show that SW has a significant negative impact on innovation performance, and the interaction term coefficient between enterprise ego-network density and SW is positively significant, meaning whole cooperation network small-world characteristics SW enhance the negative impact of ego-network density on innovation performance. Upon analyzing current research results, it is found that whether high clustering or short path length in small-world networks, only when maintained at an appropriate level do they positively impact innovation performance; once exceeding this level (or threshold), the impact reverses.

To deeply explore the influence mechanism of small-world characteristics, CC_{ratio} and PL_{ratio} are separately added as moderating variables to the model. Model 7 results show that CC_{ratio} has a significant negative impact on innovation performance, and the interaction term coefficient between enterprise ego-network density and CC_{ratio} is positively significant, meaning the network average clustering coefficient ratio enhances the negative impact of ego-network density on innovation performance. Model 8 results show that PL_{ratio} has a positive impact on innovation performance but is not significant ($p=0.234>0.05$), and the interaction term coefficient between ego-network density and PL_{ratio} is negative, indicating that the network average shortest path length ratio weakens the negative impact of ego-network density on innovation performance, though not significantly ($p=0.223>0.05$). Under small-world structures, highly clustered relationships lead to closer cooperation, while long path lengths can bring fresh, non-redundant information. Thus, in the enhancing effect of whole cooperation network small-world characteristics on the relationship between ego-network density and innovation performance, the clustering coefficient plays a greater role than path length, with clustering coefficient having an enhancing effect and path length having a weakening effect, consistent with theoretical analysis. Therefore, Hypothesis 4b is supported.

Additionally, according to the Akaike Information Criterion (AIC), smaller AIC values indicate better models. Table 5 shows that Models 6 and 7 have AIC values of 5428.6 and 5428.3, respectively, the smallest among all models, indicating that the moderating effect of whole cooperation network small-world characteristics is very obvious.

5.4 Model Robustness Analysis

To verify the robustness of the statistical model, this paper conducts statistical analysis on dependent variables with 2-year and 3-year lags, with results shown in Tables 6 and 7 . The negative binomial regression results show that enterprise technological innovation accumulation, whole network density, and enterprise betweenness centrality have significant positive impacts on innovation performance with 2-year and 3-year lags. Enterprise ego-network scale and cooperation partners have significant positive impacts on innovation performance with 2-year and 3-year lags, while enterprise ego-network density has significant negative impacts. Therefore, Hypotheses 1, 2, and 3 are all supported. Model 5 analysis results for 2-year and 3-year lags are consistent with 1-year lag results. Model 6, 7, and 8 analysis results show that the significance level of the positive moderating effect of small-world characteristics on the relationship between ego-network density and innovation performance decreases from 0.01 to 0.05 but remains significant. This indicates that the theoretical model constructed in this paper has strong robustness and is not greatly affected by time lag factors.

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6 Research Conclusions and Discussion

6.1 Research Conclusions

Although research on the impact of patent cooperation network small-world characteristics on enterprise technological innovation performance has received widespread attention, the influence mechanism remains unclear. This paper takes 165 enterprises in the speech recognition technology field as research objects, constructs patent cooperation networks from 1990-2014 based on co-patentee relationships, uses enterprise ego-network characteristics as independent variables and whole cooperation network small-world characteristics as moderating variables, and empirically analyzes the complex relationships among ego-networks, whole cooperation network small-world characteristics, and enterprise technological innovation performance. Compared with existing research, this paper's contributions are mainly reflected in the following aspects:

(1) The negative binomial regression model results show that in the speech recognition technology field's patent cooperation network, enterprise ego-network scale has a significant positive impact on innovation performance, indicating that more cooperation partners benefit innovation; ego-network density has a significant negative impact, indicating that while expanding cooperation scale, enterprises need to maintain moderate network embeddedness to avoid excessive trust and dependence on existing social relationships and prevent knowledge redundancy caused by overly high network density; cooperation with small companies promotes innovation performance, indicating that small companies can provide fresh, heterogeneous information and knowledge.

(2) The negative binomial regression model results show that in the speech recognition technology field's patent cooperation network, the influence mechanism of small-world characteristics differs from theoretical analysis and previous research conclusions. Whole cooperation network small-world characteristics have no significant moderating effect on the relationship between ego-network scale and innovation performance; whole cooperation network small-world characteristics have a significant positive moderating effect on the relationship between ego-network density and innovation performance. Further analysis reveals that the clustering coefficient plays a positive moderating role, while path length plays a negative moderating role (though not significant).

Small-world characteristics, as typical features of whole cooperation networks, enhance the negative impact of enterprise ego-network density on innovation performance through their high clustering coefficient.

6.2 Discussion and Research Prospects

The limitations of this study include: (1) It only focuses on the speech recognition technology field, and the research sample needs to be expanded to verify the universality of findings; (2) It only includes enterprises as research subjects, lacking research on other innovation entities such as universities and research institutes. Future research will expand the scope in two directions: first, further distinguishing ego-network density to explore the impact of small-world characteristics on different density levels; second, further distinguishing small-world characteristics to explore how different degrees of small-world characteristics affect enterprise technological innovation performance.

Therefore, to improve enterprise technological innovation performance, three suggestions are proposed: First, enterprises should expand ego-network scale as much as possible, as more cooperation partners benefit technological innovation, especially those with certain cognitive distance who can enhance enterprises' ability to absorb heterogeneous information through knowledge complementarity. Currently, industry-university-research cooperation is flourishing, and enterprises should continuously strengthen cooperation and exchanges with universities and research institutes to find more suitable, high-quality partners. Second, enterprises should guard against information redundancy caused by overly close ego-networks, as patent cooperation network small-world characteristics will strengthen this negative effect. R. S. Burt's structural holes theory suggests that when individuals act as network "gatekeepers," they enhance control over network information and obtain higher returns. Therefore, when formulating R&D cooperation strategies, enterprises should try to position themselves as gatekeepers, maintain ego-network density within a moderate range, avoid excessive network embedding, and prevent excessive time and resource costs in maintaining multiple social relationships. Third, enterprises should value cooperation with small companies and startups, especially in artificial intelligence fields where these companies often master cutting-edge technologies.

Through project-based cooperation, enterprises can supplement their technological advantages, thereby enhancing innovation performance. Compared with large company cooperation, competitive cooperation risks with small companies are significantly lower.

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Author Contributions

Guan Peng: Proposed research ideas, responsible for literature review, data analysis, and paper writing.
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Fu Zhu: Participated in discussing research ideas and providing revision suggestions.
Ye Longsheng: Participated in data analysis and model construction.

Note: Figure translations are in progress. See original paper for figures.