

# Study on the Impact of Boundary-Spanning Search on Breakthrough Innovation in Enterprises

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## Abstract

Breakthrough innovation is crucial for enterprises to overcome developmental constraints, establish sustained competitive advantages, and achieve long-term growth. This study investigates the relationship between boundary-spanning search and breakthrough innovation, incorporating knowledge coupling as a mediator and digital-intelligent empowerment as a moderator. Using survey data from 355 firms in China's strategic emerging industries, empirical analysis yields three main findings: (1) Boundary-spanning search positively influences breakthrough innovation. (2) Boundary-spanning search enhances knowledge coupling, which partially mediates the link between boundary-spanning search and breakthrough innovation. (3) Digital intelligent empowerment positively moderates the impact of boundary-spanning search on knowledge coupling and amplifies the mediating role of knowledge coupling in the boundary-spanning search-breakthrough innovation relationship. By examining these dynamics in the context of rapid digital and intelligent technological advancement, this study extends theoretical perspectives on breakthrough innovation and provides practical guidance for enterprises to effectively utilize boundary-spanning search, optimize knowledge coupling mechanisms, and leverage digital-intelligent technologies.

## Keywords

Breakthrough Innovation; Boundary-spanning Search; Knowledge Coupling; Digital Intelligent Empowerment.

## 1. Introduction

Amid industrial transformation, firms face challenges including accelerating technological iteration, market volatility, diversifying consumer demand, and shortening product lifecycles [1]. Incremental innovation alone is insufficient for enhancing competitiveness. Radical innovation generates disruptive impacts for firms and nations, enabling the development of core technologies and overcoming industrial bottlenecks. In the knowledge economy, firm innovation centers on acquiring, integrating, and reconfiguring knowledge elements. Constructing a coherent knowledge system depends fundamentally on creative recombination. Thus, radical innovation is the knowledge-guided reconstruction of value systems, with knowledge flow and integration intrinsically linked to its efficiency. Individual firms are often constrained by resources, capabilities, perspectives, and knowledge gaps [2], rendering a "lone wolf" model inadequate for advancing radical innovation. This necessitates cross-boundary knowledge collaboration. Acquiring and integrating external knowledge is therefore crucial. Yet, research presents inconsistent conclusions on how boundary-spanning search influences radical innovation. Due to differing objectives, search focus varies, leading to disparate outcomes. Boundary-spanning search may create path dependency, solidifying core capabilities and organizational form, ultimately inhibiting radical innovation [3]. Thus, this relationship warrants further investigation.

While boundary-spanning search broadens knowledge horizons, it also introduces fragmentation and integration challenges, making knowledge coupling critical. Knowledge coupling involves integrating and reconfiguring heterogeneous information, facilitating tacit-explicit knowledge transformation. This process bridges information advantages and innovative outcomes, accelerating radical innovation. With rapid digital technology development (AI, cloud computing, mobile internet), organizational boundaries are increasingly open [4]. Digital intelligence technologies are increasingly significant for innovation. Therefore, this study introduces digital intelligence empowerment as a moderator between boundary-spanning search and knowledge coupling. In summary, this paper examines the relationship between boundary-spanning search and radical innovation, analyzing the mediating mechanism of knowledge coupling and the moderating effect of digital intelligence empowerment, aiming to enrich radical innovation research.

## 2. Research Hypothesis

### 2.1. Boundary-Spanning Search and Radical Innovation

Boundary-spanning knowledge search enables firms to acquire and absorb external technological spillovers, facilitating cross-domain integration and synthesis of global scientific resources [5], thereby enhancing overall innovation capability. Boundary-spanning search allows firms to internalize heterogeneous knowledge [6], broadening technological cognitive boundaries and enabling breakthroughs. This stimulates exploration and innovation capabilities while directly contributing to technological outcomes. Through exposure to cutting-edge technologies, firms accumulate diverse knowledge elements, increasing recombination potential and helping overcome internal R&D bottlenecks [7]. Accessing and integrating heterogeneous knowledge from multiple fields enables firms to transcend existing cognitive frameworks and develop more innovative products.

H1: Boundary-spanning search positively affects radical innovation.

### 2.2. The Mediating Role of Knowledge Coupling

Knowledge coupling capability encompasses the abilities related to knowledge acquisition, integration, and creation, thereby expanding the breadth of a firm's external knowledge sources [8]. This facilitates the construction of dense and multi-layered knowledge networks, enabling firms to establish innovation niche advantages in the short term. In the process of advancing radical innovation, a critical pathway involves conducting cross-domain knowledge search and acquisition, followed by the systematic recombination and integration of knowledge elements from diverse technological sources. This fundamental transformation of the knowledge structure is essential for driving such innovations [9].

H2: Knowledge coupling plays a partial mediating role in the relationship between boundary-spanning search and radical innovation.

### 2.3. The Moderating Role of Digital Intelligence Empowerment

AI enhances value creation through deep market insights and real-time process optimization, reducing trial-and-error costs and encouraging investment in breakthrough technologies [10]. As a transformative search paradigm, AI automates and accelerates resource identification while improving matching accuracy via data-driven mechanisms [11]. It expands technological combinations, accelerating cross-domain knowledge fusion and reconfiguration. Furthermore, digital intelligence technologies-big data, cloud computing, and IoT-enable firms to transcend internal silos, deepening and broadening organizational information exchange [12].

H3: Digital intelligence empowerment positively moderates the relationship between boundary-spanning search and knowledge coupling.

H4: Digital intelligence empowerment positively moderates the mediating effect of knowledge coupling in the relationship between boundary-spanning search and radical innovation.

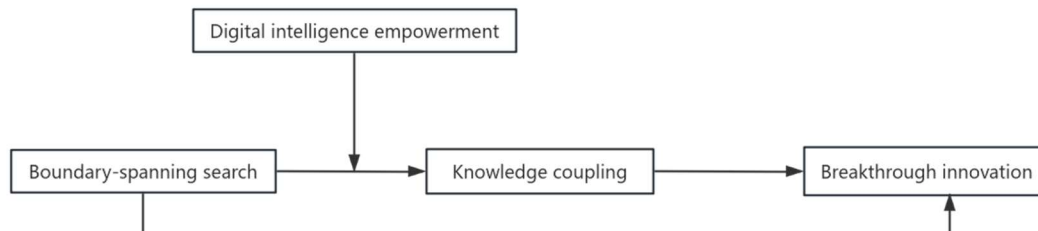


Figure 1. Theoretical model

### 3. Empirical Research

#### 3.1. Variable Measurement

To ensure reliability and validity, all scales were adapted from established instruments widely used in prior research. A pilot survey was conducted with relevant firms and professionals to assess content appropriateness and clarity. All items were measured on a five-point likert scale (1 = strongly disagree, 5 = strongly agree), with higher scores indicating greater agreement or satisfaction.

**Boundary-Spanning Search:** Boundary-spanning search is measured across 12 items from the perspective of knowledge source origins [13].

**Breakthrough Innovation:** This study examines how boundary-spanning search and knowledge coupling drive technological breakthroughs and market disruption, measuring breakthrough innovation through technological change magnitude, substitutability, and consumption pattern shifts [14].

**Knowledge Coupling:** This paper adopts the fundamental definition of knowledge coupling established in prior research, establishing a scale comprising seven items from the perspectives of knowledge deepening reconstruction and knowledge expansion reconstruction [15].

**Digital Intelligence Empowerment:** Based on the definition of digital intelligence empowerment, which refers to the integration and convergence of digital and intelligent technologies, this study adopts a well-established scale for big data analytics-powered artificial intelligence (BDA-AI), consisting of 10 items [16].

**Control Variables:** This study includes four main control variables. Based on the experience of previous scholars, firm age, firm size, firm nature, and industry type are employed as control variables in this research.

#### 3.2. Data Collection

To ensure scale validity, a pilot study was conducted prior to the formal survey. Respondents were required to be middle or senior managers familiar with their firm's external search and internal knowledge coupling activities. After confirming scale reliability and validity, 420 questionnaires were distributed, yielding 380 returns. After excluding invalid responses (e.g., patterned answers, missing data, overly short completion times), 355 valid questionnaires were obtained, with an effective response rate of 93.42%. Harman's single-factor test extracted four common factors, with the first factor explaining 33.627% of the variance—below the 40% threshold—indicating no serious common method bias.

### 3.3. Reliability and Validity Testing and Descriptive Statistical Analysis

First, SPSS 27.0 was used to test scale reliability and validity (Table 1). Cronbach's  $\alpha$  for all four variables exceeded 0.7, indicating good reliability. As all items were adapted from established scales, content validity is satisfactory. For construct validity, KMO values exceeded 0.7 and factor loadings ranged from 0.6 to 0.8, confirming adequate construct representation. Composite Reliability (CR) and Average Variance Extracted (AVE) were calculated based on factor loadings. All AVE values exceeded 0.5, indicating good convergent validity, and CR values exceeded 0.7, confirming high internal consistency.

**Table 1.** Reliability and validity test results of the scale

Scaled variable	Variable item	factor loadings	KMO	Cronbach's $\alpha$	CR	AVE
Boundary-spanning search	Q1-Q12	0.712-0.790	0.908	0.888	0.889	0.572
Breakthrough innovation	Q13-Q18	0.756-0.828	0.919	0.906	0.907	0.619
Knowledge coupling	Q19-Q25	0.698-0.777	0.917	0.894	0.894	0.547
Digital intelligent empowerment	Q26-Q35	0.724-0.789	0.959	0.925	0.925	0.554

Secondly, Pearson's correlation coefficient method was employed to analyse the correlations among variables in the valid questionnaires. Table 2 presents the Pearson correlation coefficients, means, and standard deviations for the primary variables. Testing via the variance inflation factor (VIF) revealed that all VIF values were below 5, indicating no multicollinearity issues existed between the variables.

**Table 2.** Descriptive statistics of variables

Variable	1	2	3	4	5	6	7	8
1.Nature of Business	1							
2.Enterprise Size	-0.442**	1						
3.Industry Sector	-0.018	0.035	1					
4.Company Longevity	0.117*	-0.126*	0.099	1				
5.Boundary-spanning search	-0.038	0.108	-0.01	0.002	1			
6.Knowledge coupling	-0.057	0.118*	-0.075	-0.03	0.314**	1		
7.Digital intelligent empowerment	-0.021	0.153**	0.032	-0.029	0.384**	0.306**	1	
8.Breakthrough innovation	-0.055	0.184**	0.004	0.042	0.478**	0.479**	0.461**	1
Mean	1.997	2.942	2.425	2.046	3.972	3.721	4.041	3.835
Standard Deviation	0.862	1.103	1.127	0.733	0.823	0.838	0.879	0.837

### 3.4. Hypothesis Testing

In this study, all research hypotheses were tested using SPSS 27.0. A regression model analysis was conducted with firm nature (ownership type), industry type, firm size, and firm age as control variables, boundary-spanning search as the independent variable, knowledge coupling as the mediating variable, digital intelligence empowerment as the moderating variable, and radical innovation as the dependent variable.

#### 3.4.1. Main Effect Test

First, we set radical innovation as the dependent variable and included industry type, firm age, size, and ownership as control variables (Model 1) to control for confounding effects. In Model 2, we added boundary-spanning search as the independent variable.

Results show that in Model 1, control variables had limited and mostly insignificant effects on radical innovation. In Model 2, boundary-spanning search exhibited a significant positive effect on radical innovation ( $\beta = 0.468$ ,  $p < 0.001$ ), supporting H1.

### 3.4.2. Mediation Effect Test

#### (1) Mediation Test Based on Stepwise Regression

To examine whether knowledge coupling mediates the relationship between boundary-spanning search and radical innovation, this study first employed hierarchical stepwise regression analysis for preliminary verification, followed by bootstrap analysis for further validation. First, the causal relationship between the independent variable (boundary-spanning search) and the dependent variable (Breakthrough innovation) was tested in the main effect analysis (Model 2). Second, the relationship between boundary-spanning search and the mediator (knowledge coupling) was examined. With knowledge coupling as the dependent variable, the four control variables were entered to establish Model 3. Subsequently, boundary-spanning search was introduced as an independent variable to form Model 4.

Third, to further verify the mediating role of knowledge coupling, we constructed a complete mediation model by adding knowledge coupling to the baseline model. Model 5 tested the effect of knowledge coupling on radical innovation with knowledge coupling as the independent variable. Model 6 introduced knowledge coupling as a mediator based on Model 2 (the effect of boundary-spanning search on Breakthrough innovation).

**Table 3.** Hierarchical regression analysis results of variables

variable	Breakthrough innovation				Knowledge coupling			
	Model 1	Model 2	Model 5	Model 6	Model 3	Model 4	Model 7	Model 8
<b>Control Variable</b>								
Nature of Business	0.028	0.031	0.031	0.032	-0.005	-0.004	-0.016	-0.006
Enterprise Size	0.163* *	0.122**	0.120**	0.101*	0.089	0.057	0.036	0.051
Industry Sector	-0.007	0.001	0.021	0.02	-0.058	-0.052	-0.058	-0.061
Company Longevity	0.078	0.082	0.082	0.084	-0.008	-0.005	-0.002	0.006
<b>Independent variable</b>								
Boundary-spanning search		0.468***		0.336***		0.359***	0.294***	0.311***
<b>Mediating Variable</b>								
Knowledge coupling			0.490***	0.368***				
<b>Moderating Variable</b>								
Digital intelligent empowerment							0.202***	0.249***
<b>Interaction Term</b>								
Boundary-spanning search×Digital intelligent empowerment								0.134*
R <sup>2</sup>	0.039	0.236	0.253	0.341	0.02	0.148	0.183	0.446
ΔR <sup>2</sup>	0.027	0.224	0.241	0.328	0.008	0.135	0.168	0.199
F	3.239*	19.692* **	21.563* **	27.391* **	1.654	11.090* **	11.910* **	11.250* **

As shown in Table 3, in Model 3, which included only control variables, the regression results indicated that these variables had a limited effect on knowledge coupling, with relatively small coefficients and mostly insignificant p-values, suggesting that background variables did not directly and significantly influence knowledge coupling. In Model 4, boundary-spanning search was introduced as an independent variable, revealing a significant positive effect on knowledge coupling ( $\beta = 0.359, p < 0.001$ ). In Model 5, knowledge coupling demonstrated a significant positive effect on radical innovation ( $\beta = 0.490, p < 0.001$ ), supporting H3. In Model 6, when knowledge coupling was introduced as a mediator, the coefficient of boundary-spanning search on radical innovation decreased from 0.468 to 0.336, while remaining significant ( $p < 0.001$ ). Additionally, knowledge coupling continued to exert a significant positive effect on radical innovation ( $\beta = 0.368, p < 0.001$ ). These results indicate that knowledge coupling partially mediates the relationship between boundary-spanning search and radical innovation, thus supporting H2.

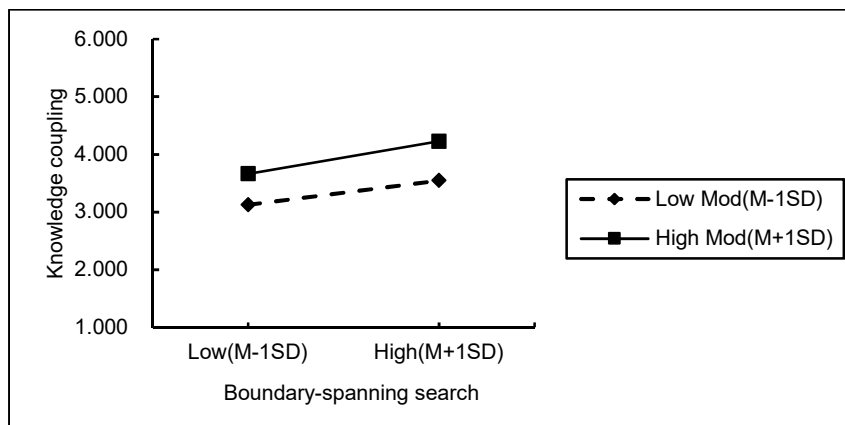
(2) Mediation Test Based on Bootstrap Analysis

To further examine the mediating effect of knowledge coupling, this study employed the Bootstrap method (with 5,000 resamples) using Model 4 in the PROCESS macro (Version 4.2) for SPSS. The detailed results are presented in Table 4.

**Table 4.** Bootstrap mediation effect results

Pathway	Type of Effect	Effect	BootSE	95% CI	
				Lower Bound	Upper Bound
Boundary-spanning search→Knowledge coupling→Breakthrough innovation	Indirect Effect	0.132	0.028	0.081	0.191
	Direct Effect	0.336	0.052	0.234	0.437
	Total Effect	0.468	0.052	0.367	0.57

**3.4.3. Moderation Effect Test**



**Figure 2.** Moderating Effects of Digital Intelligence Empowerment

To test the moderating effect, multiple regression models (Models 7 and 8) were established with knowledge coupling as the dependent variable, incorporating boundary-spanning search, digital intelligence empowerment, and their interaction term. Detailed results are presented in Table 3. Model 7 examined the effects of boundary-spanning search and digital intelligence empowerment on knowledge coupling. Model 8 further included the interaction term to test the moderating effect of digital intelligence empowerment on the relationship between boundary-spanning search and knowledge coupling. As shown in Table 3, in Model 8, the interaction term between boundary-spanning search and digital intelligence empowerment had a significant positive effect on knowledge coupling ( $\beta = 0.134, p < 0.05$ ), indicating that

digital intelligence empowerment positively moderates the relationship between boundary-spanning search and knowledge coupling. Thus, Hypothesis H3 is supported.

To illustrate the moderating effect more clearly, we divided digital intelligence empowerment into high and low groups (mean  $\pm$  1 SD) and plotted the simple slope analysis graph based on the statistical results.

#### 3.4.4. Moderated Mediation Effect Test

This study employed the Bootstrap method to test the moderated mediation effect using the PROCESS macro in SPSS 27.0. The detailed results are presented in Table 5.

**Table 5.** Moderated mediation effect test results of variables

Pathway	Type of Effect	Effect	BootSE	95% CI	
				Lower Bound	Upper Bound
Boundary-spanning search→Knowledge coupling→Breakthrough innovation	Low (-1 SD)	0.073	0.026	0.024	0.13
	High (+1 SD)	0.156	0.034	0.092	0.226
	Difference (High - Low)	0.083	0.008	0.068	0.096

Results show that under high digital intelligence empowerment, the mediating effect of knowledge coupling between boundary-spanning search and radical innovation was 0.156, with a 95% confidence interval excluding zero [0.092, 0.226]. Under low digital intelligence empowerment, the mediating effect was 0.073, with a 95% confidence interval excluding zero [0.024, 0.130]. The difference between the high and low groups was 0.083, with a 95% confidence interval excluding zero [0.068, 0.096]. These findings indicate that digital intelligence empowerment positively moderates the mediating role of knowledge coupling in the relationship between boundary-spanning search and radical innovation, supporting Hypothesis H4.

## 4. Conclusion

This paper investigates how boundary-spanning search affects radical innovation, introducing knowledge coupling as a mediator and digital intelligence empowerment as a moderator, thereby constructing a moderated mediation model. The study arrives at the following findings: (1) Boundary-spanning search significantly enhances radical innovation performance. (2) Knowledge coupling plays a crucial mediating role in the relationship between boundary-spanning search and radical innovation. (3) Digital intelligence empowerment positively moderates the relationship between boundary-spanning search and knowledge coupling.

The theoretical contributions of this study are threefold. First, it extends research on boundary-spanning search and radical innovation by addressing a relatively under-explored area, particularly the limited attention paid to innovation modes characterized by high uncertainty and originality. Second, it elucidates the bridging role of knowledge coupling between boundary-spanning search and radical innovation, clarifying the core pathway of knowledge transformation. By positioning knowledge coupling as a mediator, this study adopts a holistic perspective encompassing knowledge deconstruction, matching, and recombination, thereby revealing its bridging function in the value conversion of heterogeneous knowledge. Third, it expands the understanding of boundary conditions in the boundary-spanning search–radical innovation relationship. Introducing digital intelligence empowerment as a moderator provides novel insights for nuanced research on innovation management in the digital era.

The managerial implications are as follows. First, firms should establish precise boundary-spanning search mechanisms to build a solid resource foundation for radical innovation.

Second, they should develop systematic knowledge coupling mechanisms to provide critical support for radical innovation. Third, they should create synergistic digital intelligence empowerment mechanisms to accelerate radical innovation.

Despite these contributions, this study has limitations. It only considers digital intelligence empowerment as a contextual variable, whereas innovation activities are often shaped by multiple internal and external contextual factors. Future research could incorporate these diverse contextual variables to construct a multi-factor interaction framework, thereby revealing the complex driving mechanisms of radical innovation from an integrated multidimensional perspective.

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