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Intangible capital and urban innovation capability: Evidence from China

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Abstract: Intangible capital has become an increasingly important driver of value creation and innovation in the digital economy, yet its role in shaping urban innovation capability remains insufficiently understood. Drawing on the Corrado – Hulten – Sichel (CHS) framework, this study classifies intangible capital into three dimensions: computerized information capital, innovative capital, and economic competency capital. Using a two-way fixed effects model, the study examines the impact of intangible capital on urban innovation capability in China. To ensure the reliability of the findings, the analysis further incorporates endogeneity tests, robustness checks, mediation analysis, and heterogeneity analysis across different city tiers. The results indicate that intangible capital exerts a significant positive effect on urban innovation capability. In addition, the findings suggest that this effect operates partly through enhanced R&D investment intensity. These results provide new evidence on the role of intangible assets in promoting urban innovation and offer important implications for innovation-driven development in emerging economies.

Keywords: intangible capital; measurement Indicators; innovation; China

JEL codes：O32；O17；O18

1. Introduction

Under the rapid expansion of the digital economy and artificial intelligence, intangible capital has become an increasingly important source of economic growth and innovation. In many advanced economies, including European countries such as Spain and Italy, the foundation of long-term competitiveness is shifting from tangible assets toward knowledge-based and intangible assets (Gumbau - Albert, 2024). This transition is particularly evident in economies undergoing structural transformation, where innovation capacity plays a critical role in sustaining productivity growth and technological upgrading.

China has entered a stage of high-quality economic development in which innovation is regarded as a major driver of economic transformation (Chen & Naughton, 2016). In recent years, the Chinese government has promoted a series of science and technology initiatives aimed at strengthening innovation capability and improving the allocation efficiency of innovation resources. Policies emphasizing technological self-reliance under the 14th Five-Year Plan, together with the expansion of smart city strategies and digital infrastructure, reflect the growing importance of innovation in China's modernization process. Despite continuous increases in R&D expenditure, however, substantial regional disparities in innovation performance persist across Chinese cities. In some regions, high levels of innovation investment coexist with relatively weak knowledge conversion efficiency and limited innovation output (Wu et al., 2022). These challenges suggest that traditional growth models relying primarily on fixed capital accumulation and land-driven expansion are becoming increasingly unsustainable, thereby highlighting the need to identify new drivers of urban innovation.

Against this backdrop, intangible capital has attracted growing attention as a strategic resource for innovation and economic development. According to the Corrado–Hulten–Sichel (CHS) framework, intangible capital includes computerized information capital, innovative capital, and economic competency capital (Corrado et al., 2009). Compared with traditional tangible assets, intangible capital is characterized by stronger knowledge spillovers, cumulative effects, scalability, and lower marginal costs. With the development of digital technologies and knowledge-intensive industries, investment in intangible assets has expanded rapidly at both firm and national levels. Data from the World Intellectual Property Organization (WIPO) indicate that intangible capital investment accounted for nearly 14% of global GDP in 2024, exceeding tangible capital investment at approximately 11%. Existing studies suggest that intangible assets such as software, organizational knowledge, and R&D activities can improve productivity and innovation performance at the firm level (Haskel & Westlake, 2017), while also contributing to regional innovation ecosystems and urban knowledge spillovers (Glaeser, 2012).

Nevertheless, the relationship between intangible capital and urban innovation capability remains insufficiently understood. First, existing studies primarily focus on firms or national economies, while relatively limited attention has been paid to the urban dimension of intangible capital accumulation. Second, previous research often treats intangible capital as a homogeneous concept, with insufficient distinction among different forms of intangible assets and their heterogeneous impacts on innovation capability. Third, although innovation investment is widely recognized as an important channel linking capital accumulation and innovation performance, the mechanisms through which intangible capital influences urban innovation remain underexplored. In addition, differences in economic development levels, industrial structures, and innovation environments across cities may lead to substantial heterogeneity in the effects of intangible capital.

To address these gaps, this study applies the Corrado – Hulten – Sichel (CHS) framework to classify intangible capital into computerized information capital, innovative capital, and economic competency capital, and empirically examines their effects on urban innovation capability in China using a two-way fixed effects model. The analysis further explores the mediating role of R&D investment intensity and investigates heterogeneity across different city tiers. By examining the role of intangible capital in urban innovation, this study provides new evidence on the transformation of innovation drivers in emerging economies and offers insights for innovation-oriented urban development policies.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature and develops the analytical framework. Section 3 introduces the empirical strategy, data sources, and variable definitions. Section 4 presents the empirical findings and mechanism analysis. Section 5 concludes the study and discusses policy implications.

2 Literature Review

2.1 Intangible Capital and Measurement Indicators

Research on intangible capital has primarily focused on its conceptualization, classification, and impacts. At the micro level, it refers to non-physical resources such as knowledge, information, and experience; assets that lack tangible form but generate long-

term value for their holders. At the macro level, it is broadly defined as any form of capital that does not take physical form (Corrado et al.,2013). Scholars have proposed different classification systems depending on the research context. For instance, Bollen et al. (2005) divided intangible capital into human, structural, and relational capital, while Maditinos et al. (2010) expanded the dimensions to include market, reputational, trust, and renewal capital. Corrado et al. (2022), through the widely used CHS accounting framework, categorized intangible capital into computerized information capital, innovative capital, and economic competency capital. In line with this framework, this study defines intangible capital as non-physical assets accumulated and maintained through investment, characterized by identifiability, clear ownership, and the capacity to generate future economic benefits. It adopts the CHS classification of computerized information capital, innovative capital, and economic competency capital.

Empirical research has concentrated on two main areas. At the micro level, studies examine the impact of intangible capital on firm performance. Investment in intangible assets such as innovation, organizational, and reputational capital provides firms with competitive advantages, fosters incremental growth, and supports high-quality development by facilitating access to external resources and a favorable operating environment (Rico & Cabrer-Borrás, 2020). Intangible capital influences firm behavior and strategy, with intellectual property and its transformation into productive assets playing a central role in innovation. Accumulating intangible capital enables firms to enhance efficiency, manage customer relationships more effectively, and meet operational demands. Differences in the allocation efficiency of intangible capital have been identified as a significant cause of productivity disparities among firms (Moule & Schiersch, 2023). Moreover, firms rich in intangible assets are better positioned to leverage digital technologies. For example, Goldar and Parida (2017) found a strong positive effect of intangible capital on firm productivity, particularly in manufacturing sectors with higher ICT capital intensity.

At the macro level, research highlights the role of intangible capital in driving economic growth. Building on the CHS framework and the Solow growth model, scholars have estimated the contribution of intangible capital stock to national growth. Evidence

shows that intangible investment significantly enhances economic performance, with economic competency capital contributing most strongly to labor productivity (Roth & Thum, 2013; Chen, 2018). Manufacturing remains the most intangible-intensive industry, where rising intangible investment is closely linked to total factor productivity growth. More broadly, national comparative advantages are shifting toward innovation-driven production. Notably, intangible capital, often serving as stable collateral, responds more resiliently to economic shocks than physical assets.

A review of the literature reveals that, despite substantial progress in defining intangible capital and identifying factors influencing innovation capacity, most studies remain focused on the four dimensions of the innovation capacity framework and their effects on urban innovation. Few explore the mechanisms through which intangible capital shapes urban innovation, and existing work is primarily concentrated at the national or industry level.

This paper makes four key contributions to the literature. First, it expands innovation theory by examining the relationship between intangible capital and regional innovation. By extending the traditional single-industry CHS framework to a three-industry model, the study systematically evaluates intangible capital in the Yangtze River Delta. It analyzes its role in shaping urban innovation. Second, it reveals R&D investment intensity as a critical mechanism through which intangible assets influence urban innovation, thereby deepening the understanding of how intangible capital affects regional innovation outcomes. Third, the study explores city-level heterogeneity by assessing differences in the impact of intangible capital across cities with varying innovation conditions. Finally, it provides practical insights for policy and regional development by offering both theoretical support and empirical evidence to help governments better appreciate the value of intangible capital and optimize the allocation of innovation-related resources.

2.2 Urban Innovation Capacity and Influencing Factors

Innovation capacity, widely recognized as a key driver of modern economic growth, has attracted significant scholarly attention. It is generally defined as the comprehensive ability of a region or organization to transcend traditional growth models through creative

thinking and practical action—generating new ideas, solving complex problems, and ultimately creating value. Regional innovation capacity emerges collectively from the efforts of enterprises and other innovators, with tacit knowledge embedded within these actors serving as a primary source (Foss, 1996). It can be assessed through both innovation outputs and efficiency at different stages of the innovation process (Guan & Chen, 2010).

Theoretical frameworks on regional innovation capacity typically emphasize four dimensions: innovation foundations, industrial clusters, innovation environment, and inter-factor linkages. Existing studies often analyze the determinants of innovation capacity within these categories. From the perspective of innovation foundations, human capital is paramount. Higher education systems are particularly influential in advancing economic growth and innovation in developing economies. Talent mobility across regions injects new momentum into urban innovation, while the "agglomeration effect of talent" not only generates new ideas but also attracts further talent inflows, helping to sustain the innovation ecosystem.

From the industrial cluster perspective, innovation is driven by the mobilization and application of knowledge. Industrial clusters facilitate the formation of regional innovation networks, and the specialized division of labor within clusters encourages collaborative innovation among diverse economic actors (Vial, 2019). Effective value co-creation fosters a supportive ecosystem that continuously enhances regional innovation performance. Digital industrial clusters, enabled by big data, cloud computing, and related technologies, further expand the diversity of participants and stimulate innovation through knowledge spillovers and cross-sector collaboration.

From the innovation environment perspective, industrial structure, institutional arrangements, and infrastructure play crucial roles. Industrial upgrading reallocates resources, provides specialized services and advanced management expertise, and improves both innovation output and efficiency (Wang et al., 2023; Zheng et al., 2023). Corporate digital transformation strengthens information disclosure, thereby improving innovation efficiency (Li et al., 2023; Wang & He, 2024). Government support also serves as an important catalyst: subsidies can reduce uncertainty around R&D, raise the probability of success (Latan et al., 2020), and signal credibility to external investors (Wu

et al., 2021). For instance, quantity-based subsidies tied to patent numbers have been shown to increase the volume of firm-level innovation (Cao et al., 2024). Meanwhile, digital infrastructure reduces geographical and organizational barriers within innovation networks, promotes resource sharing, and improves overall efficiency (He & Hamori, 2024).

Finally, from the perspective of inter-factor linkages, innovation capacity results from the dynamic interaction among multiple elements. Digital inclusive finance addresses the diverse financing needs of innovative enterprises, supports the commercialization of research outcomes, and strengthens the foundation for long-term innovation performance. Moreover, the collaboration between innovation actors, such as technology firms and universities, interacts with regional openness and other environmental factors to shape overall innovation capacity (Mitze & Strotebeck, 2019).

2.3 The Relationship between Intangible Capital and Innovation Capacity

China's economic development model has shifted from factor- and investment-driven growth toward an innovation-driven paradigm. Intangible capital has become a vital driver of modern economic growth, with global corporate investment in this area expanding rapidly since the 1980s, particularly in private R&D, electronic information, and artificial intelligence. As a fundamental resource for the sustainable survival and innovative development of firms, intangible capital links directly to innovation, which itself is embedded within broader social structures and environments. Innovation is not only a technological process but also a social and knowledge-based one, shaped by the acquisition and creation of new ideas.

The relationship between intangible capital and innovation capacity can be understood in several ways. First, the scalability of intangible capital reshapes firms' cost structures, with strengthened economies of scale enabling cost reductions through market expansion. Second, intangible capital reallocates resources through signaling mechanisms, channeling them toward more efficient sectors and thereby fostering innovation-oriented development models. Third, intangible capital reshapes urban innovation networks through knowledge spillovers and platform effects, with cultural soft power serving as a

binding force that enhances collaboration within these networks. At the firm level, investments in R&D and human capital generate intellectual property, which is subsequently commercialized, scaled, and branded. These outcomes of intangible capital accumulation enhance market competitiveness, sustain long-term firm development, and strengthen both urban innovation capacity and the broader innovation process.Accordingly, Hypothesis 1 is proposed:

H1: *Intangible capital effectively enhances urban innovation capacity.*

According to endogenous growth theory, R&D investment is a central driver of technological progress and knowledge accumulation, with its intensity directly shaping the capacity of firms and regions to explore new technologies and develop new products (Romer, 1990). Advanced R&D equipment and complex technical processes, however, require complementary high-skilled labor, which in turn compels firms to increase both the demand for and training of skilled talent. This process enhances overall labor productivity while amplifying knowledge spillovers (Acemoglu & Restrepo, 2018). The optimization of human capital and the resulting productivity gains provide a strong foundation for improving urban innovation capacity. Higher labor productivity not only increases resource utilization efficiency and value creation but also generates higher profits, supplying firms with the internal funding necessary to sustain long-term innovation activities.Accordingly, Hypothesis 2 is proposed:

H2: *Intangible capital influences urban innovation capacity by increasing the intensity of R&D investment.*

3 Models, Variables, and Data

3.1 Models

Before selecting the appropriate model, an F-test was conducted, and the results indicated that the two-way fixed effects model was the most suitable specification for this study. Following Bartolucci et al. (2024), the within-group estimation method for the two-way fixed effects model was adopted to control for both time effects and individual heterogeneity. Accordingly, this paper employs a two-way fixed effects model to examine the impact of intangible capital on urban innovation capacity. The baseline model is

specified as Equation (1):

$$Innovation_{it}=\beta_0+\beta_1 Intangible_{it}+\sum_{j=2}^{n}\beta_j X_{ijt}+\lambda_i+V_t+\varepsilon_{it} \quad (1)$$

Where i and t respectively represent the city and year, Innovation represents the urban innovation capacity. Intangible is the intangible capital stock. X_{ijt} represents various control variables, including human capital (HumanC), industrial structure level (TertiaryI), economic development level (PGDP), cultural development (Cultural), resident income (Income), and employment level (Employ). λ_i represents city fixed effects, v_t represents time fixed effects, and ε_{it} is the random error term. β_0 is the constant term, and β_1 and β_i indicate the direction and magnitude of the effects of intangible capital and the control variables on the innovation capacity of the 41 cities in the Yangtze River Delta region. To assess potential multicollinearity, a Variance Inflation Factor (VIF) test was conducted. The mean VIF value was 4.56, well below the conventional threshold of 10, suggesting that multicollinearity is not a concern in the model specification.

3.2 Variables Selection

(1) Explained Variable

The level of urban innovation capacity is measured by the China Regional Innovation Index published by Peking University (Zhu et al., 2024). The index adopts a firm-centric perspective and is constructed around three core elements: entrepreneurs, capital, and technology. It evaluates regional innovation and entrepreneurial vitality across five dimensions: (1) the number of new enterprises, (2) attraction of foreign investment, (3) attraction of venture capital, (4) number of patents granted, and (5) number of trademark registrations.

In building the index, big data concepts and technologies are applied. Using firms as the central market entities, the index integrates data from national industrial and commercial enterprise registrations, VCPE databases, patent databases, and trademark databases. This integration enables a comprehensive evaluation of regional performance in firm creation, investment activity, and innovation output, thereby providing a systematic measure of regional innovation and entrepreneurship vitality.

(2) Core Explanatory Variables

There is no universally accepted framework for measuring intangible capital. It is generally understood as non-physical yet identifiable capital. Intangible capital is characterized by complex interrelationships, and the absence of standardized classification. Its valuation often depends on institutional contexts and the characteristics of specific entities. This study calculates different types of intangible capital by combining available expenditure data with estimated investment conversion rates (Corrado et al., 2009).

Drawing on the methods of Zheng and Yang (2020) and the CHS framework, this study divides intangible capital into three categories: computerized information capital, innovative capital, and economic competency capital. Under this framework, based on the proxy method of relevant output data, the intangible capital stock of 41 prefecture-level cities in the Yangtze River Delta region is calculated. To ensure comparability across time, all intangible capital data are deflated using 2010 as the base year, thereby mitigating distortions from inflation and broader socio-economic changes.

Detailed classification schemes and calculation methods are provided in the Appendix. The specific indicators for measuring intangible capital are presented in Figure 1 and Table 1.

(3) Control Variables

To account for other factors that may influence urban innovation capacity, several control variables are included in the model. Human capital(HumanC) is measured by the proportion of students enrolled in regular higher education institutions relative to the total city population(Zhang et al., 2020; Han et al., 2021). The GDP of a city's tertiary industry as a share of total GDP is used to assess its industrial structure(TertiaryI). Per capita GDP (pgdp) is an important indicator of the level of economic development, while cultural development (Cultural) is proxied by the collection size of public libraries in each prefecture-level city. The income level (Income) is measured by the per capita disposable income of urban residents, and the employment level (Employ) is assessed by the proportion of employment in the secondary and tertiary industries relative to total employment.

Table 1 Intangible Capital Measurement Indicators

Primary Indicator	Secondary Indicator	Tertiary Indicator	Description
Intangible Capital	Computerized Information Capital	Software Products	The revenue from software products (e.g., operating systems and databases)
	Innovative Capital	Scientific R&D	Research and development expenditures in industries such as natural science, cultural and creative industries
		Mineral Exploration	Investment in geological exploration
	Economic Competency Capital	Brand Capital	Advertising and market research expenditure accounts for about 3% of the total revenue of the leasing and business services sector
		Firm-Specific Human Capital	A certain proportion of the total salary
		Organizational Capital	80% of management consulting revenue

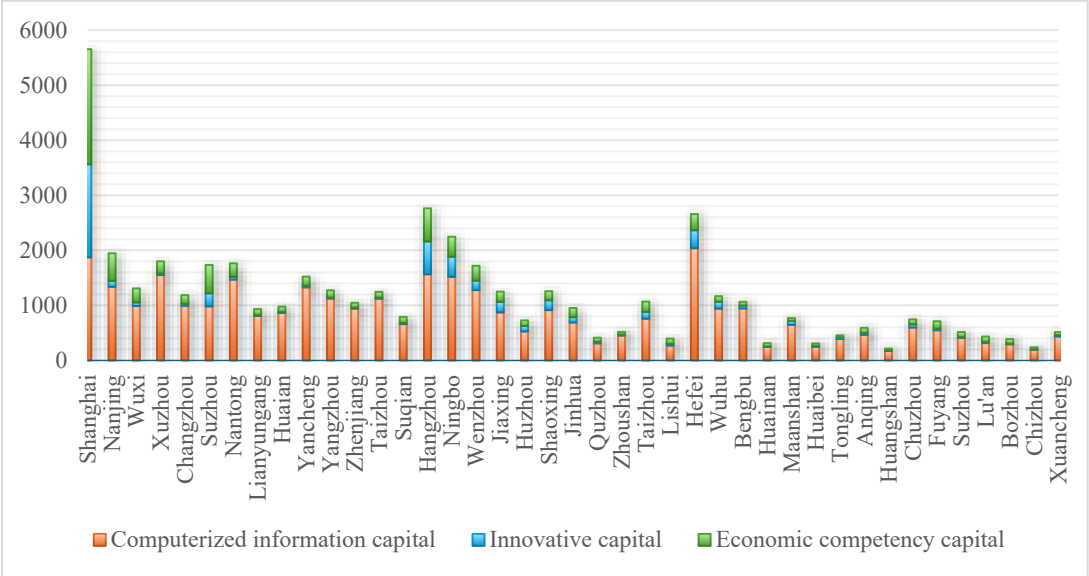


Figure 1 Intangible Capital Stock of 41 Cities in the Yangtze River Delta in 2020 (Unit：Hundred million Chinese yuan)

3.3 Data Sources

To examine the impact of intangible capital on regional innovation vitality, this study analyzes data from 41 prefecture-level cities in the Yangtze River Delta region over the period 2010–2020. Intangible capital and related variables were calculated for each city across the study period. The primary data sources include the CSMAR database, the *China Statistical Yearbook*, the *China Statistical Yearbook on Science and Technology*, and publications from the National Bureau of Statistics, which together provide comprehensive coverage of

economic indicators, human capital, innovation output, and other relevant variables. The definitions and descriptive statistics of all variables employed in the analysis are reported in Table 2.

Table 2 Descriptive Statistics of Variables

Type	Variables	Unit	Obs	Mean	SD	Min	Max
Explained variable	Innovation (Innovation capacity)	/	451	89.09	10.46	51.38	100.00
Explanatory variable	Intangible(Intangible capital)	Hundred million Chinese yuan	451	540.20	712.61	82.95	5653.43
Control variable	HumanC (Human capital)	%	451	2.08	2.15	0.16	12.72
	TertiaryI(Industrial structure level)	%	451	43.89	8.51	23.36	73.15
	PGDP(Economic development level)	Chinese yuan	451	66012.05	37694.96	9068.61	199017.84
	Cultural (Cultural development)	Thousand volumes	451	5615.15	11935.00	200.00	80630.00
	Income(Income level)	Chinese yuan	451	33645.52	12330.88	12757.26	73615.43
	Employ(Employment level)	%	451	76.01	12.82	44.81	97.49

4 Results and Discussion

4.1 Regression Results

The regression results reported in Column (1) of Table 3 show a significant positive correlation between the innovation capacity (Innovation) and intangible capital (Intangible) at the 1% level. After controlling for both time and city fixed effects, as shown in Column (2), the positive impact of intangible capital on innovation capacity remains statistically significant. This suggests that higher levels of intangible capital significantly enhance urban innovation capacity, thereby improving innovation performance.

Table 3 Two-Way Fixed Effects and Endogeneity Tests

Variables	(1)Innovation	(2)Innovation	(3)Innovation	(4)Innovation
Intangible	7.18***	5.52**	8.24***	9.05**
	(-3.03)	(-2.45)	(-3.62)	(-4.3)

HumanC		-0.61		0.73
		(-0.86)		(-1.26)
TertiaryI		0.36***		0.47
		(-3.63)		(-0.38)
PGDP		2.89		0.01
		(-1.49)		(-4.85)
Cultural		1.63**		0.42
		(-2.01)		(-2.65)
Income		-24.22***		-27.43**
		(-3.35)		(-11.82)
Employ		0.40***		0.07
		(-4.45)		(-0.31)
l.HumanC			-0.17	
			(-0.26)	
l.TertiaryI			0.36***	
			(-3.48)	
l.PGDP			0.21	
			(-0.1)	
l.Cultural			3.00***	
			(-3.83)	
l.Income			-17.44***	
			(-2.65)	
l.Employ			0.26***	
			(-3.1)	
l.Innovation				0.41***
				(-0.14)
_cons	-78.42	127.20	24.60	104.97
	(-1.42)	(-1.43)	(-0.3)	(-107.47)
city	YES	YES	YES	
year	YES	YES	YES	
N	451	451	410	410
R^2	0.81	0.84	0.84	

Notes: t-statistics are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

In addition, the share of the tertiary industry in GDP, employment development level, and cultural development all exhibit significant positive coefficients, highlighting their important roles in strengthening urban innovation capacity. These results confirm Hypothesis H1, indicating that intangible capital plays a crucial role in enhancing the innovation capacity of cities in the Yangtze River Delta. Nevertheless, possible concerns remain regarding reverse causality and omitted variable bias. For example, higher talent levels may promote innovation, but innovative regions may also attract more talent and

generate higher incomes. To address these issues, the study employs the instrumental variable method and system GMM estimation method to mitigate endogeneity.

Column (3) presents results with all control variables lagged by one period. The impact of intangible capital on innovation capacity remains significant at the 1% level, while the share of the tertiary industry in GDP, employment development level, and cultural development all remain positively associated with innovation, consistent with the baseline regression. Column (4) reports the system GMM estimation results. The coefficient for intangible capital is 9.05 and is significant at the 5% level. The AR(2) and Hansen test p-values are both above 0.1, indicating no evidence of serial correlation and supporting the validity of the model specification.

4.2 Robustness Tests

To verify the reliability and validity of the empirical results, four robustness checks were conducted: (1) replacing the explained variable, (2) adding control variables, (3) excluding specific years, and (4) adjusting the sample period.

First, the explained variable was replaced. Since the number of high-tech enterprises (NHTE) is widely recognized as a reliable indicator of urban technological development and innovation capacity, it was used as an alternative dependent variable. As reported in Column (1) of Table 4, NHTE exhibits significant positive correlations with intangible capital, human capital, the share of the tertiary industry in GDP, resident income and cultural development, confirming the robustness of the baseline findings. Second, additional control variables were included. Specifically, the proportion of the secondary industry in GDP (SecondT) and population density (PopD) were added to the original model. The results in Column (2) of Table 4 indicate that the innovation capacity remains significantly and positively correlated with intangible capital, along with the secondary industry share, employment level and tertiary industry share. This further supports the stability of the empirical conclusions. Third, to minimize potential bias from atypical years, data from 2019, marked by the economic disruptions of the COVID-19 pandemic, were excluded. As shown in Column (3) of Table 4, the intangible capital has positive impact on innovation capacity, while control variables such as employment level also remain

positively associated, lending further credibility to the results.

Table 4 Robustness Tests

Variables	(1)NHTE	(2)Innovation	(3)Innovation	(4)Innovation
Intangible	15.23***	8.53***	5.67**	5.11***
	(-3.59)	(-10.68)	(-2.23)	(8.96)
HumanC	1.50**	-0.64***	-0.13	-0.29**
	(-1.98)	(-4.71)	(-0.16)	(-2.44)
TertiaryI	1.43***	0.52***	0.34***	-0.02
	(-4.85)	(-4.56)	(-2.92)	(-0.45)
PGDP	-18.30***	-0.45	1.03	-0.04
	(-3.51)	(-0.39)	(-0.42)	(-0.06)
Cultural	15.48***	0.76	1.88**	0.25
	(-4.74)	(-1.27)	(-2.11)	(0.57)
Income	34.24***	-7.40***	-24.13***	3.30*
	(-2.81)	(-3.42)	(-3.23)	(1.78)
Employ	-0.14	0.18***	0.44***	0.01
	(-0.53)	(-3.71)	(-4.63)	(0.02)
SecondT		0.32***		
		(-3.47)		
PopD		-0.01***		
		(-8.15)		
_cons	-627.1***	-79.66***	136.80	-60.37***
	(-4.06)	(-2.90)	(-1.43)	(-2.74)
city	YES	YES	YES	YES
year	YES	YES	YES	YES
N	451	450	410	205
R^2	0.63	0.79	0.84	0.73

Notes: t-statistics are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Finally, the sample period was shortened to the most recent five years (2016–2020) to examine the short-term effects of intangible capital on innovation. The regression results in Column (4) of Table 4 show that the coefficients for intangible capital, resident income, and other controls remain significantly positive. Taken together, the results of all four robustness tests are consistent with the baseline model, indicating that the findings of this study are both stable and reliable.

4.3 Heterogeneity Analysis

To further investigate the relationship between intangible capital and urban innovation capacity in the Yangtze River Delta region, we conducts sub-sample regression according to city grades and categories of intangible capital.

For the city-tier analysis, the 41 cities in the Yangtze River Delta were grouped into two categories[1]. "Class 1 cities" (including new first-tier and second-tier cities, 15 in total) and "Class 2 cities" (third- to fifth-tier cities, 26 in total). Columns (1) and (2) of Table 5 present the results. In Class 1 cities, the coefficient for intangible capital is 2.45 and significant at the 5% level, indicating that a 1% increase in intangible capital raises the urban innovation index by 0.025. HumanC is also significant at the 5% level, with a coefficient of 0.15, suggesting that human capital contributes meaningfully to innovation outcomes in higher-tier cities. In contrast, for Class 2 cities, the coefficient for intangible capital is 8.49 and significant at the 1% level, indicating that a 1% increase in intangible capital stock boosts the innovation index by 8.49%. Additionally, the share of the tertiary industry in GDP shows a significant positive effect, underscoring the role of industrial structure in supporting innovation.

Although the coefficients for intangible capital are positive in both city groups, grouped regression coefficients cannot be compared directly (Lian & Liao, 2017). Therefore, a test for differences between groups was conducted using the seemingly unrelated estimation (SUEST) method. The p-value for the group difference is 0.000, significant at the 1% level, confirming substantial heterogeneity between Class 1 and Class 2 cities.

Table 5 Heterogeneity Analysis

Variables	(1)Class1	(2)Class2	(3)Innovation-1	(4)Innovation-2	(5)Innovation-3
Intangible	2.45**	8.49***			
	(2.55)	(8.30)			
HumanC	0.15**	-0.55	-0.43	-0.93	-0.35**
	(2.10)	(-1.22)	(-0.64)	(-1.39)	(-2.36)

[1] The Class 1 cities includes: Shanghai, Nanjing, Wuxi, Xuzhou, Changzhou, Suzhou, Nantong, Hangzhou, Ningbo, Wenzhou, Jiaxing, Shaoxing, Jinhua, Taizhou and Hefei; The Class 2 cities include Lianyungang, Huai 'an, Yancheng, Yangzhou, Zhenjiang, Taizhou, Suqian, Huzhou, Quzhou, Zhoushan, Lishui, Wuhu, Bengbu, Huainan, Ma 'anshan, Huaibei, Tongling, Anqing, Huangshan, Chuzhou, Fuyang, Suzhou, Lu 'an, Bozhou, Chizhou and Xuancheng.

TertiaryI	-0.09**	0.23***	0.36***	0.45***	-0.03
	(-2.09)	(2.88)	(-3.81)	(-4.74)	(-0.53)
PGDP	1.02	1.67	2.05	4.14**	5.92***
	(1.13)	(1.13)	(-1.11)	(-2.27)	(-5.57)
Cultural	0.58	1.73**	1.05	1.39*	1.54**
	(1.18)	(2.06)	(-1.34)	(-1.8)	(-2.29)
Income	0.87	-5.19*	-22.06***	-18.49***	-8.65***
	(0.32)	(-1.77)	(-3.19)	(-2.67)	(-3.79)
Employ	0.07	0.12**	0.38***	0.38***	0.17***
	(1.21)	(2.12)	(-4.50)	(-4.49)	(-3.23)
lncomputer			9.85***		
			(-6.47)		
lnInnovation				-2.45***	
				(-6.85)	
InEconomy					4.29***
					(-5.9)
_cons	9.09	-110.00***	96.16	212.20***	36.44
	(0.24)	(-3.14)	(-1.26)	(-2.92)	(-1.53)
city	YES	YES	YES	YES	YES
year	YES	YES	YES	YES	YES
N	165	286	451	451	451
R^2	0.68	0.77	0.85	0.85	0.73

Notes: t-statistics are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Columns (3) to (5) of Table 5 examine the effects of the three components of intangible capital, computerized information capital, innovative capital, and economic competency capital, on the innovation capacity. The results show that both computerized information capital and economic competency capital are significantly positively correlated with the innovation capacity at the 1% level, with coefficients of 9.85 and 4.29, respectively, suggesting that increases in these forms of capital strongly enhance regional innovation performance. By contrast, the coefficient for innovative capital is negative (-2.45), indicating a suppressing effect on the innovation capacity. This result may reflect inefficiencies in the allocation of innovative capital, structural mismatches within the innovation system, or insufficient investment in basic research, all of which constrain original breakthroughs and limit long-term innovation performance.

4.4 Mediation Effect

Building on the previous analysis, a mediation effect model is constructed to examine the specific pathway through which intangible capital influences regional innovation capacity. R&D investment intensity (RDI) is selected as the mediating variable for the mechanism test. Following the classical three-step approach, three models are specified for empirical testing: (2), (3), and (4).

$$Innovation_{it} = \alpha_0 + \alpha_1 Intangible_{it} + \sum_{j=2}^{n} \alpha_j X_{ijt} + \lambda_i + V_t + \varepsilon_{it} \quad (2)$$

$$RDI_{it} = \varphi_0 + \varphi_1 Intangible_{it} + \sum_{j=2}^{n} \varphi_j X_{ijt} + \lambda_i + V_t + \varepsilon_{it} \quad (3)$$

$$Innovation_{it} = \gamma_0 + \gamma_1 Intangible_{it} + \gamma_2 RDI_{it} + \sum_{j=3}^{n} \gamma_j X_{ijt} + \lambda_i + V_t + \varepsilon_{it} \quad (4)$$

In Models (3) and (4), RDI_{it} represents the mediating variable, while the remaining specifications are consistent with the baseline regression model. As shown in Column (2) of Table 6, the regression coefficient between intangible capital and R&D investment intensity is 0.01 and significant at the 10% level, indicating that intangible capital promotes R&D investment. When RDI is introduced into the regression model (Column 3 of Table 6), intangible capital and R&D investment intensity are significant at the 1% level and 5% level, with coefficients of 6.31 and 25.19, respectively. This finding confirms the presence of a partial mediation effect: intangible capital enhances urban innovation capacity not only directly but also indirectly by stimulating R&D investment. As R&D intensity increases, urban innovation capacity improves continuously, thereby fostering sustainable urban development.

Table 6 Mediation Effect Test

Variables	(1)Innovation	(2)RDI	(3)Innovation
Intangible	5.52**	0.01*	6.31***
	(-2.45)	(-1.82)	(-7.85)
HumanC	-0.61	0.01***	-0.61***
	(-0.86)	(-5.20)	(-4.13)
TertiaryI	0.36***	-0.01***	0.09
	(-3.63)	(-3.12)	(-1.64)

PGDP	2.89	0.02***	2.53**
	(-1.49)	(-4.42)	(-2.51)
Cultural	1.63**	0.01	0.93
	(-2.01)	(-0.16)	(-1.50)
Income	-24.22***	0.01	-4.95**
	(-3.35)	(-0.30)	(-2.15)
Employ	0.40***	-0.01***	0.17***
	(-4.45)	(-4.78)	(-3.23)
RDI			25.19**
			(-2.33)
_cons	127.20	-0.24*	-56.52*
	(-1.43)	(-1.83)	(-1.93)
city	YES	YES	YES
year	YES	YES	YES
N	451	451	451
R^2	0.84	0.27	0.75

Notes: t-statistics are reported in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

5 Conclusions and Policy Implications

Based on panel data from 41 cities in the Yangtze River Delta urban agglomeration between 2010 and 2020, this study systematically examined the impact of intangible capital on urban innovation capacity using a two-way fixed effects model, mediation analysis, and heterogeneity analysis. The main conclusions are as follows.

First, intangible capital exerts a significant positive effect on urban innovation capacity. Both baseline regressions and multiple robustness tests confirm that increases in intangible capital significantly enhance the urban innovation capacity, supporting Hypothesis H1. In the context of the digital economy, intangible capital has become a core driver of urban innovation, with characteristics such as knowledge spillovers, cumulativeness, and low marginal costs contributing to the optimization of regional innovation ecosystems. Second, heterogeneity analysis reveals marked differences across city tiers and types of intangible capital. The promoting effect of intangible capital is stronger in second-tier cities than in first-tier cities, suggesting that developed cities may be encountering diminishing marginal returns on innovation inputs or structural bottlenecks. Among the three components of intangible capital, computerized information

capital and economic competency capital have significant positive effects on innovation capacity. In contrast, innovative capital shows a negative relationship, likely due to inefficiencies in resource allocation, low patent conversion rates, or insufficient investment in basic research. Third, mechanism analysis demonstrates that intangible capital enhances urban innovation capacity by increasing R&D investment intensity, thereby validating Hypothesis H2. The intangible capital not only directly promotes innovation but also indirectly influences it by stimulating R&D activities.

However, the study has certain limitations. First, the study is confined to the Yangtze River Delta, and the applicability of the conclusions to other regions in China requires further verification. Second, the measurement of intangible capital remains incomplete, as it does not fully capture all relevant dimensions. Future research could refine the measurement system by incorporating multi-source and higher-frequency data. Drawing on these conclusions, several policy recommendations are proposed. (1) Strengthen regional sci-tech cooperation: The three provinces and one municipality (Jiangsu, Zhejiang, Anhui, and Shanghai) should jointly design innovation development strategies to avoid redundant construction and resource waste. A regional platform for sharing innovation resources should be promoted to enhance knowledge flow and collaborative innovation among enterprises, universities, and research institutions. (2) Increase investment in and cultivation of intangible capital: Governments should guide funding toward areas such as software, databases, brand development, and organizational management, with particular attention to supporting the accumulation of intangible capital in underdeveloped cities. At the same time, improving intellectual property protection and conversion efficiency will enhance the effective contribution of innovative capital. (3) Optimize the innovation ecosystem: Establish and improve diversified science and technology financing systems, design financial products suited to the needs of innovative enterprises, and foster a cultural environment that encourages risk-taking and tolerates failure. Strengthening the soft power of an innovation culture will further stimulate the vitality of multiple innovation actors. (4) Implement differentiated innovation policies: Tailored policies should be developed according to city tiers and capital types. Class 1 cities should focus on improving innovation quality and structural optimization, while Class 2 cities can

continue to expand the scale of intangible capital. Simultaneously, efforts should be made to improve the allocation efficiency of innovative capital and to increase investment in basic research and industry–university–research collaboration.

Data availability

The data used in this study are available from the corresponding author upon reasonable request

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Appendix

Measurement Methods for Intangible Capital

Drawing on the method of Zheng and Yang (2020) and the CHS framework, and considering the local characteristics of the Yangtze River Delta urban agglomeration, this study uses a proxy method based on relevant output data to estimate intangible capital investment, categorizing intangible capital into computerized information capital, innovative capital, and economic competency capital.

1.Computerized Information Capital

The China Statistical Yearbook does not report software and database expenditures separately but includes them in a broader industry category encompassing information services, computer services, and the software industry. In contrast, the China Electronic Information Industry Statistical Yearbook (Software Section) provides more detailed data. Therefore, this study uses the revenue from software products (e.g., operating systems and databases) recorded in the Software Section as a proxy for computerized information capital investment. This approach is highly consistent with the CHS method.

2.Innovative Capital

Data for this category mainly comes from the China Statistical Yearbook on Science and Technology, which reports R&D expenditures in multiple fields, including natural sciences, mineral exploration, cultural and creative industries, etc. Its coverage is largely consistent with the CHS definition of innovative capital, and the reported R&D expenditures are used directly to calculate investment in this category.

3.Economic Competency Capital

According to the CHS framework, economic competency capital consists of three key components: brand capital, human capital, and organizational capital.

•Brand Capital: CHS defines brand capital as the sum of advertising expenditure and market research. However, detailed statistical records in this regard are lacking in the Yangtze River Delta, similar to other regions. The China Statistical Yearbook does not separate advertising and market research expenditure but includes it under the major category of "Leasing and Business Services" within the tertiary industry. This study assumes that advertising and market research expenditure accounts for about 3% of the total revenue of the leasing and business services sector, based on data from the China Economic Census Yearbook, to approximate brand capital investment.

•Human Capital: Human capital is divided into education expenditure and employee training. While there are no direct statistics on employee training expenditure, the China Statistical Yearbook reports total wages and employment numbers by region. According to the Implementation Regulations of the Enterprise Income Tax Law, enterprise employee education expenditure shall not exceed 2.5% of the total wages. Based on this regulation, this study estimates human capital investment by applying the 2.5% ratio to the total wage bill in the Yangtze River Delta region.

• Organizational Capital: Organizational capital is divided into purchased and internally generated parts. Purchased organizational capital typically includes management consulting expenditure. Although management consulting revenue is not directly reported, the China Economic Census Yearbook estimates that management consulting accounts for about 75% of the revenue of the "Leasing and Business Services" sector within the tertiary industry. Based on this, management consulting revenue for each city is estimated, and following Corrado et al. (2013), 80% of this revenue is treated as

purchased organizational capital investment. Internally generated organizational capital is often proxied by a certain percentage of executive compensation. Corrado et al. (2013) suggest using 20% of executive salaries, while Marrano et al. (2009) refined this method by considering managers in specific sectors like communications and information. In addition, further excluding management wages from sectors like agriculture and computer services. However, given the limited classification of wage data across different industries in Chinese official statistics and to avoid potential double-counting, this study does not calculate internally generated organizational capital separately.

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