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Digital transformation, entrepreneurship, and disruptive innovation: evidence of corporate digitalization in China from 2010 to 2021

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The year 2010 was an important turning point for China's economy, and the digital economy has become its new feature. In the digital economy wave, digital transformation and innovation are two essential starting points for enterprise development. Few studies have examined the effect of companies' digital transformation on disruptive innovation, neglecting the role of entrepreneurship. This study aims to address this research gap by developing an analytical framework for digital transformation, entrepreneurship, and disruptive innovation. Based on China's A-listed firms from 2010 to 2021, we use Python to create indicators for digital transformation and examine its impact on disruptive innovation and the role of entrepreneurship using a double fixed-effects model. The results demonstrate that digital transformation significantly promotes disruptive innovation, and entrepreneurship positively moderates this relationship. Furthermore, heterogeneity analyses show that digital transformation's positive effects of disruptive innovation and entrepreneurship are more pronounced in non-SOEs, companies in growth and decline stages, and nonmanufacturing companies. However, in SOEs and manufacturing firms, entrepreneurship was unable to moderate this relationship. The conclusions reflect the exploration of the realization mechanism and micro-foundations of the current, in-depth digital transformations, and the findings provide reference guidelines for enabling enterprises to realize digital transformation and disruptive innovation and, relevant experiences.

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Introduction

In China, 2010 marked a significant turning point. Since then, China's growth has declined, the economy has been restructured, and the effects of previous stimulus policies linger. This period is known as the "three phases superimposed," reflecting a distinctive feature of China's economic development. Moreover, labor force growth has been declining steadily since 2010 (Cai 2016). Importantly, throughout history, economic growth has always accompanied a labor force expansion. China, however, has broken the norm by growing its economy even as the size of its labor force declines. The reason behind this anomaly lies in the development of the digital economy. Digitalization has broken the mechanical limits of economic growth and radically transformed the degree of logic and value creation of the business community (Bertani et al. 2021).

The digital economy has become one of the main engines driving China's economic growth. China achieved a remarkable milestone in advancing the digital economy in 2021[1], as the size of its digital economy surged to an impressive 45.5 trillion yuan, marking a substantial 13.6% year-on-year increase in nominal terms. This phenomenal growth rate accounted for a significant 39.8% of the country's gross domestic product (GDP), exemplifying the immense impact and prominence of digitalization in China's economic landscape.

In the tide of the digital economy, digital transformation is not an "optional" issue but rather a "mandatory" direction to take for corporates to survive and thrive in the long run. The incorporation of digital transformation is vital for the integration and advancement of business objectives. By implementing digital transformation, enterprises can effectively address the issue of information asymmetry, enhance, and broaden integration and collaboration channels, accelerate innovative output, and infuse more vitality into their operations. Within this context, clarifying the connection between digital transformation and high-quality innovation in corporations is meaningful.

After reviewing existing studies, some significant results on the mechanisms of the digital transformation of enterprises on innovation can be grouped into three main categories. First, some researchers explore digitalization from a dynamic capabilities perspective to accelerate innovation by enhancing dynamic capabilities such as information communication, knowledge sharing, knowledge usage, and rapid response (Mikalef and Pateli 2017; Cenamor et al. 2019; Dremel et al. 2020). Second, some studies explore the firm lifecycle, where the impact of digital transformation on the innovation of firms at different lifecycle stages is significantly differentiated (Klepper 1996; Markard 2020), and where firms at different lifecycle stages balance costs, rewards, and threats of innovation models in an integrated manner (Kang et al. 2017; Si et al. 2021). Third, researchers explore the ability of digital transformation to enhance productivity in resource management (Ritter and Pedersen 2020), accelerate information integration, and improve information disclosure (Chen et al. 2022) from a financing constraint perspective, thereby reducing information processing costs for investors (Pagani and Pardo 2017) and helping firms quickly obtain financing.

Although the abovementioned studies have examined how digital transformation impacts companies' innovation, they rest mainly on general technological innovation, and more discussion is needed on whether digital transformation can promote disruptive innovation. More empirical evidence is needed starting from the micro level of firms. In addition, the current mechanism research takes mainly the perspective of the organization's internal and external environment while ignoring the role of entrepreneurship. However, entrepreneurship enables entrepreneurs to unleash their autonomy and creativity, opening new economic possibilities and promoting business success. With the advent of digitalization, the private sector has steadily and consistently strengthened its market position, with non-state-owned enterprises (non-SOEs) becoming as influential as SOEs. Numerous ambitious and innovative entrepreneurs have emerged, forming a keystone of Chinese entrepreneurship. Based on the above observations and theoretical discussions, whether implementing digital transformation can accelerate the pace of disruptive innovation through entrepreneurship at the enterprise level is also a topic of interest in this paper.

This paper's marginal contributions and main findings include the following: (1) we integrate digital transformation, entrepreneurship, and disruptive innovation into a unified logical system; (2) from the perspective of constructing and increasing the degree of entrepreneurship, we study the facilitating contribution of digital transformation to disruptive innovation, reveal the innovation effect created by digital transformation, broaden the research ideas of breakthrough corporate innovation in the era of the digital economy, and provide new perspectives from which firms can promote disruptive innovation; and (3) we conduct heterogeneity tests based on enterprise property rights, industries, and life cycles to show that the positive effects of digital transformation on disruptive innovation and entrepreneurship are more pronounced in non-SOEs, in enterprises' in growth and decline stages, and in nonmanufacturing enterprises. These findings open a new exact mechanism with which to analyze the link between digital transformation and disruptive innovation. The findings provide a theoretical basis and a practical perspective for promoting entrepreneurship and breakthrough innovation in enterprises.

Literature review and hypotheses

Digital transformation and disruptive innovation. Digitization has been the dominant aspect of China's economic progress over the last ten years. Various sectors in China have undergone a revolutionary shift due to the Internet. Thus, there is a significant need for digital transformation at both the industrial and enterprise levels (Li et al. 2017). Enterprises anticipate that digital transformation will stimulate disruptive innovation, foster the emergence of novel business forms and models, and enhance the quality, efficiency, and degree of resource allocation within the industry (Wan et al. 2015).

Digital transformation is a way in which to use digital technology and capabilities to drive the reconstruction of an organization's business model and business ecosystem. Digital transformation has two cores: technology and organizational change. From a technological perspective, digital transformation is the application of information technology in a company's production process (Goerzig and Bauernhansl 2018), the process of driving change and innovation in the way in which a company operates its production services (Zhang et al. 2022), and the utilization of digital technologies and devices for major operational improvements (Fitzgerald et al. 2014). From an organizational change perspective, digital transformation focuses on changes in organizational processes and business models (Loonam et al. 2018) to improve business performance by changing the path of corporate value creation through digital technologies (Vial 2019; Ribeiro 2021). Overall, digital transformation is a way in which to handle and use digital techniques, technologies, and capabilities to drive organizational model innovation and ecosystem reconfiguration to achieve business transformation, innovation, and growth (Coskun-Setirek and Tanrikulu 2021; Akter et al. 2022). Digital transformation is profoundly changing the innovation ecosystem of enterprises, linking digital transformation and management with "structural

and value creation changes," the "use of digital technologies," "dynamic capabilities," "strategic responses," and "consumer behavior" (Kraus et al. 2022). As enterprises' digital transformation level continues to increase, their contribution to technological innovation becomes more assertive (Nambisan et al. 2017; Guo et al. 2022).

Since (Christenson 1997) introduced the concept of disruptive innovation, academics have been divided on its definition. Disruptive innovation involves "doing things differently," aiming to exploit new products and technologies through radical changes to existing products and technologies. This form of innovation is a crucial strategic tool for companies (Adner 2002), whether it be in terms of technological innovation (Danneels 2004), business model innovation (Paap and Katz 2004), or a combination of the two (Schumpeter 1934). In general, disruptive innovation creates high-performance products that replace original mainstream market products. This innovation is achieved through the utilization of new technologies or the integration and application of existing technologies from different disciplines and fields. Once successful, disruptive innovation can not only enable enterprises to dominate in terms of market share and obtain enormous profits but also foster the development of the whole industry (Laursen and Salter 2006; Foss and Saebi 2017; Dahlander et al. 2021). However, disruptive innovation requires a large number of significant risks and a high degree of tolerance for uncertainty, often also requiring rich knowledge accumulation, outstanding research and development (R&D) capabilities, and continuous large-scale capital investment (Forés and Camisón 2016). Due to the shortage of R&D funds, knowledge reserves, and excessive potential risks, many enterprises adopt the "focusing on quantity" innovation strategy. These enterprises are unwilling to innovate or challenged in terms of innovating radically (Wenjing and Manni 2016; Cao 2020).

Digital transformation plays an important facilitating role in the achievement of disruptive innovation. Relying on the inherent superiorities in cross-time and cross-space communication, data processing, and information accessibility (Wu et al. 2021), digital transformation helps enterprises integrate and reconstruct the innovation process of internal and external resources, processes, and structures. Moreover, digital transformation can effectively alleviate financing difficulties (Lee et al. 2023) and innovation risks (Jafari-Sadeghi et al. 2021) and increase the level of R&D cooperation (Lee et al. 2021; Rocha et al. 2021; Soluk and Kammerlander 2021).

In summary, we posit the following hypothesis:

H1: Digital transformation has a significant contribution to disruptive innovation in enterprises.

Moderating effect of entrepreneurship. In discussions about entrepreneurship, economists generally agree that it is a material driving force for sustained economic growth. However, there is a need for consensus on its exact meaning. Schumpeter (1934) was one of the earliest proponents of entrepreneurship, defining it as "creative destruction" and the realization of personal value. Drucker (1985) later described innovation as a unique tool and means of entrepreneurship. To provide a clear definition, Sharma (1999) extended the concept to include the creation, restructuring, or organization of internal and external innovative behaviors within an organization. In sum, Schumpeter (1934), as a representative scholar, emphasized the entrepreneurial spirit of innovation. Additionally, another perspective, based on Knight (1921) and other scholars following his lead, focused on entrepreneurs' risk-taking abilities and adventurous spirit. The above authors believed that the most crucial characteristic of entrepreneurship is risk-taking (Anwar et al. 2021). Finally, Hirschman (1965); Hirschman (1970) and scholars influenced by his work argued for a balance between cooperation and innovation, believing that cooperation is the essence of entrepreneurship (Rezazadeh and Nobari 2018; Bosse et al. 2023). Since then, many scholars have explored various aspects of entrepreneurship, such as adaptability (Zahra et al. 2006; Wu et al. 2020), openness (Slavec et al. 2017), and social responsibility (İyigün 2015; Tiba et al. 2019).

Despite its socialist system, China has also embraced a market economy, creating a constantly evolving environment and an abundance of market opportunities. Entrepreneurship is closely tied to such an abundance of market opportunities (YU 2018). The rise in the use of mobile internet technology, particularly after 2010, has given birth to new business and consumption models, altering the values of enterprises, and shaping a new market system and competitive landscape. Most entrepreneurs believe that they possess a keen understanding of the environment and are innovative. Approximately 88.6% and 86.2% of entrepreneurs, consider themselves to be "all" or "fundamentally" entrepreneurs, respectively. Furthermore, 85% of entrepreneurs believe that they are adept at seizing opportunities, and 84.2% view themselves as "completely" or "basically" adventurous and willing to take risks (Lan et al. 2019). While the social and economic environments for entrepreneurs may vary, Chinese entrepreneurship is characterized by a fearless approach to innovation and risk-taking. Additionally, Chinese entrepreneurs emphasize cooperation, dedication, and an increasing sense of social responsibility (Zhang 2018).

By synthesizing and comparing the definitions of entrepreneurship, scholars' descriptions focus mainly on three classes: innovation, risk-taking, and cooperation. The understanding of the concept of entrepreneurship lays the foundation for this study. Based on its existing definitions, this study defines entrepreneurship as the innovative conduct of economic actors who are encouraged enough to embrace risks and are open to collaboration.

Entrepreneurship is crucial for achieving disruptive innovation. The digital transformation of businesses has significantly impacted the development of the innovation and entrepreneurship ecosystem. Digital technology has brought about new opportunities for entrepreneurship and has given rise to novel types of enterprises (Bouncken and Kraus 2022; Song et al. 2022). R&D innovation is no longer limited to a single field but is characterized by cross-border collaboration. Additionally, entrepreneurial service organizations have expedited their networking development. Data-driven entrepreneurship, R&D, and services are now operating more smoothly and efficiently. Entrepreneurs play a central role in this system and must embrace their entrepreneurial spirit to establish a dynamic equilibrium system of mutually beneficial symbiosis and coordinated development with other participants, enhancing digital management innovation and ultimately focusing on disruptive innovation (Endres et al. 2022).

In summary, this paper proposes the following hypothesis:

H2: Entrepreneurship plays an active moderating role in the effect of the mechanism of digital transformation on disruptive innovation.

Research design

Sample selection and sources. Since 2010, China's economy has entered a new phase, characterized by the expansion of the digital economy strategy and infrastructure, as well as the integration of digitization concepts into various aspects of production and daily life. We select the sample period from 2010 to 2021, covering fully A-listed firms, except for those in the financial sector (based on the 2012 edition of the industry classification standard of the

Securities and Futures Commission). We obtain relevant financial and governance data from the China Stock Market & Accounting Research (CSMAR) database and Management Discussion & Analysis (MD&A) text from JUCHAO[2]. To ensure appropriate data quality, we screen the sample as follows: (1) we exclude special treatment companies; and (2) we exclude those companies with serious data deficiencies. Finally, we obtain a total of 22,200 observations. Furthermore, we winsorize the main variables of the sample to an upper and lower 1.5% tail shrinkage. We use Python for text mining and analysis during data collection and Stata15 for data processing.

Variable measurement. 1. *Explained variable*: radical innovation of enterprises (*lnCitepatent*). Based on existing research, most scholars evaluate the degree of disruptive innovation using the patent citation index. (1) Forward-citation patents refer to those patents that are later cited by other types of patents. Ahuja and Katila (2001); Baumol (2004), and Phene et al. (2006) use the forward citation frequency of patents to define disruptive technologies, pointing out that disruptive innovation reflects the ability to influence subsequent technologies. Kamuriwo et al. (2017) argue that the forward citation of patents could be used to evaluate the influence of innovative technologies. Veugelers and Wang (2019) point out that highly cited patents receive more citations because the advanced and even generic technical knowledge they contain has essential value and influence ability on subsequent technologies and can also lead the frontier of technology development. Aristodemou and Tietze (2018) constructed nine forward-citing patent indicators from the patent and patent portfolio levels to evaluate the degree of influence of innovation. (2) Backward-citation patents refer to those patents cited by focal patents. Zuo et al. (2019) believe that the number of backward-cited patents can evaluate the degree of novelty. Sharma and Tripathi (2017) argue that the frequency of citing scientific literature is fundamental to evaluating breakthroughs in technology because citations indicate that patented technology relies more on scientific knowledge than on prior art. Rosenkopf and Nerkar (2001) propose the backward patent citation perspective of the degree of differentiation between the cited patent category and the focal patent. (3) Forward and backward citations, namely, the patent citation structure, are considered. For example, Dahlin and Behrens (2005) comprehensively consider the number of forward and backward citations, pointing out that the citation structure of patents is a good standard with which to judge technological breakthroughs. Érdi et al. (2013) believe that the patent citation network reflects the innovation process and, thus, that emerging technologies can be predicted by analyzing the network structure. Linares et al. (2019) point out that the patent citation network structure can be used to identify radical innovation. A few scholars also use the "expert evaluation method" to evaluate the novelty and influence of radical innovation technology. However, due to the recency effect, such expert evaluation results may exhibit subjective bias (Benner and Tushman 2002; Salomo et al. 2008; Stiller 2019). Considering the objectivity of indicators and data availability, this paper uses the number of forward patent citations, and the number of cumulative forward cited patents within 5 years after the patent is published, as the proxy variable for radical innovation.

2. *Explanatory variable*: digital transformation (*DT_txt*). Digital transformation and engagement have attracted extensive attention from scholars, but measuring the degree of enterprise digital transformation is significantly difficult. There are three main types of methods used in existing studies. The first method measures the digitalization degree by using the proportion of the amount related to the digital economy in the details of intangible or fixed assets at the end of the year (Huai-jin et al. 2020; Shen et al. 2022; He and Chen 2023). The second method uses a questionnaire survey to describe the degree of digital transformation from different dimensions (Matt et al. 2015; Hess et al. 2016; Shen et al. 2022). The third type analyses the annual reports of enterprises by constructing a dictionary of digital-related terms through text mining and analysis and measuring the digital transformation through the proportion of related word frequency. Some typical representatives include Fei et al. (2021), Chenyu et al. (2021), and Chun et al. (2021). Since questionnaire data may be affected by questionnaire design bias and insufficient sample size and the proportion of digital-related assets reflects the infrastructure input of enterprises, this paper adopts the third method, namely textual analysis, to measure the degree of digital transformation. There are some drawbacks to using this method because the text content related to digitalization disclosed in the MD&A texts of listed companies usually reflects the concerns and expectations of enterprises on digital transformation rather than the actual results. However, this situation will not seriously interfere with the research conclusions because most listed companies have systematic errors in their annual reports (Xinyu and Xiaoling 2022). Specifically, this paper follows the method of Fei et al. (2021), which obtains the MD&A corpus from companies' annual financial reports and constructs a Chinese digital word list with 76 "digital transformation" structured feature words in Chinese MD&A texts (see the Supplementary Appendix online). This word list includes five subdimensions: "artificial intelligence technology," "big data technology," "cloud computing technology," "blockchain technology," and "digital technology application." Moreover, we build these words into the *Chinese_Digitalization.pkl* of the *cntext* library (version 1.8.0)[3]. Finally, we sum the frequency of digitalization-related words in each enterprise to calculate the percentage of these words in the MD&A text and multiply them by 100 to generate a digital transformation index (see Supplement Appendix). The greater this index value is, the stronger the degree of digital transformation. Moreover, this paper uses the ratio of digital economy assets disclosed in financial reports to the net asset value of the two assets as the proxy variable for digital transformation. Specifically, when the detailed item of intangible assets contains "software" and the detailed item of fixed assets contains "electronic equipment," "electronic computer," "communication equipment," and other keywords related to the digital economy and technology, we can calculate the proportion of this part in the total net value of intangible and fixed assets.

3. *Mediating variable*: entrepreneurship (*ENT*). Based on the previous analysis, entrepreneurship focuses on risk-taking, innovation, and cooperation. Drawing on Shaojun et al. (2014) and Xiumei et al. (2022) to construct the measure of entrepreneurship, this paper selects the indicators of self-generated capital satisfaction rate, R&D investment intensity and whether to jointly apply for patents to represent the risk-taking spirit, innovation spirit, and cooperation spirit, respectively, and uses the entropy weighting method for each indicator. The entrepreneurship index (ENT) is calculated by assigning weights to each measure through the entropy weighting method.

4. *Control variables*: Regarding the current research results, the following variables may affect the degree of disruptive innovation of firms, and thus, we control for them: firm age (*lnage*), represented by the natural logarithm of listing years the firm; nature of ownership (*soe*), assigned a value of 1 for SOEs and 0 otherwise; firm size (*lnsize*), represented by the natural logarithm of the firm's total assets; board size (*lnboard*), represented by the natural logarithm of board members; board independence (*inp*), defined as the ratio of the number of independent directors to the number of board members; top 10 shareholders' shareholding

Table 1 Variable definition and description.

Variables name	Symbol	Variables definition
Cumulative number of forward citations within five years of patent disclosure	lnCitepatent	Natural logarithm of the cumulative number of forward citations within 5 years of the patent's disclosure
Digital transformation	DT_txt	The total word frequency of 76 terms for "digital transformation" as a percentage of the total word frequency of MD&A×100
Digital transformation	DT_num	Proportion of the sum of the digitization-related components of the year-end itemized intangible assets and fixed assets to the net asset value of both, as disclosed in the notes to the financial statements of listed companies
Entrepreneurship: Adventure, Innovation, Cooperation	ENT	Self-generated funds satisfaction rate: (cash inflow from operating activities + cash and equivalents at the beginning of the period)/current cash outflow R&D investment intensity: R&D investment/operating cost Whether to jointly apply for patent: 1 for joint, 0 for otherwise
Company Age	lnage	Natural logarithm of the age of the company
Nature of ownership	soe	State-owned enterprises take 1, otherwise take 0
Company Size	lnsize	Natural logarithm of total assets
Board Size	lnboard	Natural logarithm of board members
Board Independence	inp	Percentage of independent directors
Shareholdings of top 10 shareholders	top10	Shareholdings of top 10 shareholders
Leverage	Lev	Total liabilities/total assets
Liquidity Ratio	liquid	Current assets/current liabilities
Return on Total Assets	ROA	Net profit/total assets

(*top10*), expressed as the ratio of the number of shares held by the top 10 shareholders to the total number of shares; and firm financial status, described as leverage (*Lev*), liquidity (*liquid*) and profitability (*ROA*). In addition, this paper controls for time and industry-fixed effects. Table 1 defines the specific variables used.

Model design. Equation (1) is constructed to test the influencing relationship between digital transformation and disruptive innovation.

$$\mathrm{lnCitepatent}_{it} = \beta_0 + \beta_1 \mathrm{DT}_{txt,it} + \gamma \mathrm{Controls}_{it} + \sum \mathrm{year} + \sum \mathrm{industry} + \varepsilon_{it} \quad (1)$$

Equation (2) is constructed to test the moderating mediation relationships among entrepreneurship, digital transformation, and disruptive innovation.

$$\mathrm{lnCitepatent}_{it} = \beta_0 + \beta_1 \mathrm{DT}_{txt,it} + \beta_2 \mathrm{ENT}_{it} + \beta_3 \mathrm{DT}_{txt} * \mathrm{ENT}_{it} + \gamma \mathrm{Controls}_{it} + \sum \mathrm{year} + \sum \mathrm{industry} + \varepsilon_{it} \quad (2)$$

For the above models, subscript i denotes the firm and t denotes the year. The explanatory variable $InCitepatent_{it}$ represents the firm's disruptive innovation level in year t, the core explanatory variable $\mathrm{DT}_{txt,it}$ represents the degree of digital transformation of the firm, the moderating variable ENT_{it} represents the degree of entrepreneurship, and $\mathrm{Controls}_{it}$ is the control variable matrix for firm-related characteristics. *year* and *industry* represent time and industry fixed effects, respectively, and ε_{it} is a random disturbance term.

Empirical results

Descriptive and correlation analysis. Before launching the empirical analysis, this paper conducts statistical tests on the relevant characteristics of the sample firms. Tables 2 and 3 show the obtained results. As seen from the table, the mean of disruptive innovation (*lnCitepatent*) is 0.446, and the minimum and maximum are 0 and 2.197, respectively, indicating significant differences in the levels of disruptive innovation across companies. The mean values of digital transformation (*DT_txt* and *DT_num*) are 0.0633 and 0.00228, respectively, which indicates that most Chinese companies are not deep into digital transformation. The average of entrepreneurship (ENT) is −12.38, the minimum value is −15.16, and the maximum value is −9.714, indicating different degrees of entrepreneurial spirit. Most of such enterprises are engaged in low-tier entrepreneurship. The correlation coefficients among the main variables are significantly correlated at less than 1%, which initially confirms the primary hypothesis of this paper.

Table 2 Descriptive statistics.

Variable	Obs	Mean	Std.Dev.	Min	Max
lnCitepatent	22,200	0.446	0.653	0	2.197
DT_txt	22,200	0.0633	0.133	0	0.692
DT_num	22,200	0.00228	0.00447	0	0.0237
ENT	22,200	−12.38	1.699	−15.16	−9.714
lnage	22,200	2.870	0.344	1.792	3.466
soe	22,200	0.323	0.468	0	1
lnsize	22,200	22.08	1.217	20.05	25.39
lnboard	22,200	2.235	0.170	1.792	2.639
indp	22,200	0.375	0.0520	0.333	0.556
top10	22,200	0.581	0.145	0.260	0.868
Lev	22,200	0.403	0.201	0.0571	0.857
liquid	22,200	2.663	2.667	0.435	15.22
ROA	22,200	0.0393	0.0584	−0.188	0.182

Regression results. Table 4 shows the regression results of whether corporations' degree of digital transformation promotes disruptive innovation. The results indicate that the coefficient of *DT_txt* is markedly positive at the 1% significance level, meaning that companies' degree of digital transformation has an active influence on promoting their disruptive innovation, as confirmed by H1. The implementation of a digital transformation strategy increases the degree of disruptive innovation such as by realigning and reallocating domestic and outdoor resources, processes, and structures (Warner and Wäger 2019); significantly reducing firms' R&D costs (Lyytinen et al. 2016); efficiently connecting decentralized parts; and forming new ways of delivering value (Vial 2019). Companies with higher degrees of digital transformation are more inclined to make disruptive innovation efforts than those with lower degrees of digital transformation.

Table 3 Correlation analysis.

Variable	lnCitepatent	DT_txt	DT_num	ENT	lnage	soe	lnsize
lnCitepatent	1						
DT_txt	0.064***	1					
DT_num	0.066***	0.134***	1				
ENT	0.246***	0.058***	0.047***	1			
lnage	−0.252***	−0.022***	−0.033***	−0.029***	1		
soe	−0.014**	−0.097***	0.007	0.063***	0.234***	1	
lnsize	−0.047***	−0.054***	−0.042***	0.114***	0.302***	0.370***	1
lnboard	0.068***	−0.066***	0.024***	0.060***	0.046***	0.283***	0.260***
indp	−0.036***	0.048***	0.010	−0.014**	0.003	−0.085***	−0.036***
top10	0.049***	−0.075***	0.003	−0.009	−0.212***	−0.073***	0.004
Lev	−0.069***	−0.091***	−0.037***	−0.049***	0.225***	0.320***	0.530***
liquid	0.077***	0.055***	0.008	0.046***	−0.229***	−0.221***	−0.391***
ROA	0.106***	0.010	0.036***	0.108***	−0.114***	−0.116***	−0.034***
	lnboard	indp	top10	Lev	Liquid	ROA	
lnboard	1						
indp	−0.556***	1					
top10	−0.008	0.035***	1				
Lev	0.155***	−0.031***	−0.161***	1			
liquid	−0.120***	0.015**	0.182***	−0.681***	1		
ROA	0.011	−0.014**	0.250***	−0.386***	0.265***	1	

Table 4 Baseline regression results.

	(1)	(2)	(3)
VARIABLES	lnCitepatent	lnCitepatent	lnCitepatent
DT_txt	0.257***		0.230***
	(0.0373)		(0.0371)
lnage		−0.141***	−0.142***
		(0.0140)	(0.0140)
soe		0.00339	0.00551
		(0.00973)	(0.00972)
lnsize		0.0574***	0.0556***
		(0.00440)	(0.00440)
lnboard		0.152***	0.151***
		(0.0295)	(0.0295)
indp		0.0402	0.0344
		(0.0898)	(0.0897)
top10		−0.0320	−0.0242
		(0.0289)	(0.0289)
Lev		−0.0865***	−0.0779**
		(0.0319)	(0.0319)
liquid		0.00183	0.00232
		(0.00203)	(0.00203)
ROA		0.634***	0.634***
		(0.0751)	(0.0750)
Constant	0.430***	−0.747***	−0.728***
	(0.00450)	(0.121)	(0.121)
Observations	22,200	22,200	22,200
R-squared	0.241	0.256	0.257

Standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. The following table is the same.

Robustness checks. To test the robustness of the above benchmark estimation results, this paper tests the following two aspects. First, the core explanatory variable is replaced. We use the proportion of "software" in the intangible assets detail item and "electronic equipment," "electronic computer," and "communication equipment" in the fixed assets detail item in the net value of intangible and stationary assets as the replacement index of digital transformation for robustness estimation. Second, we add control variables, among which *isduality*, *maleratio*, and *ROE* are added to reexamine the impact of the degree of digital transformation on disruptive innovation. Table 5 displays the results. Model (1) is the estimation result when replacing the digital transformation variable, and Model (2) is the estimation result when adding control variables. The results show that regardless of whether the variable is replaced or the control variable is added, the regression results are still significant, and the significance level is 1%, indicating that the hypothesis that digital transformation gives a dramatic boost to the degree of disruptive innovation is robust.

Endogeneity tests. To alleviate the possible reverse causality problem, we further lag the explanatory and control variables by one phase for regression analysis. The results show that the coefficient of digital transformation remains positive and significant at the 1% level after a one-period lag, indicating that digital transformation enhances the degree of disruptive innovation rather than disruptive innovation promoting corporations' digital transformation. H1 can still be confirmed after considering the endogeneity issue (Table 6).

Mechanism test

The mechanism research finds that digital transformation enhances the degree of disruptive innovation through entrepreneurship. This paper empirically tests the entrepreneurship effect through model (2). Table 7 shows the results. The mechanism test shows that when entrepreneurship is the moderating variable, the coefficient of the interaction term (*DT_txt*ENT*) between digital transformation and entrepreneurship is 0.0440, which is significantly positive at the 5% significance level, indicating that the mediation effect of entrepreneurship exists, i.e., that digital transformation enhances the degree of disruptive innovation through entrepreneurship; thus, H2 holds.

Further discussion

Research has found that digital transformation can help boost the degree of disruptive innovation, which can be achieved through the entrepreneurship pathway. However, disruptive innovation may have heterogeneous effects across the different natures of property rights, across industries, and across firm life cycles. Therefore, the heterogeneous effects are tested below.

Table 5 Robustness tests.

VARIABLES	(1) lnCitepatent	(2) lnCitepatent
DT_txt		0.232***
		(0.0371)
DT_num	4.470***	−0.141***
	(0.884)	(0.0140)
lnage	−0.141***	0.00572
	(0.0140)	(0.00999)
soe	0.00161	0.0550***
	(0.00973)	(0.00443)
lnsize	0.0579***	0.144***
	(0.00440)	(0.0296)
lnboard	0.145***	0.0254
	(0.0295)	(0.0899)
indp	0.0295	−0.0246
	(0.0898)	(0.0289)
top10	−0.0344	−0.0768**
	(0.0289)	(0.0319)
Lev	−0.0864***	0.00234
	(0.0319)	(0.00203)
liquid	0.00217	0.706***
	(0.00203)	(0.0904)
ROA	0.620***	0.0224**
	(0.0751)	(0.00888)
isduality		0.149***
		(0.0373)
maleratio		−0.0281
		(0.0194)
ROE		−0.829***
		(0.123)
Constant	−0.749***	−0.829***
	(0.121)	(0.123)
Observations	22,200	22,200
R-squared	0.257	0.258

Table 6 Endogeneity tests.

VARIABLES	(1) lnCitepatent	(2) lnCitepatent	(3) lnCitepatent
DT_txt_lag1	0.295***		0.258***
	(0.0401)		(0.0398)
lnage_lag1		−0.129***	−0.129***
		(0.0146)	(0.0146)
soe_lag1		0.00192	0.00433
		(0.0104)	(0.0103)
lnsize_lag1		0.0613***	0.0592***
		(0.00475)	(0.00475)
lnboard_lag1		0.124***	0.123***
		(0.0313)	(0.0312)
indp_lag1		0.0247	0.0200
		(0.0953)	(0.0952)
top10_lag1		−0.00908	−0.00143
		(0.0309)	(0.0309)
Lev_lag1		−0.0863**	−0.0770**
		(0.0341)	(0.0341)
liquid_lag1		0.00175	0.00228
		(0.00211)	(0.00211)
ROA_lag1		0.797***	0.795***
		(0.0820)	(0.0819)
Constant	0.422***	−0.831***	−0.806***
	(0.00472)	(0.129)	(0.129)
Observations	18,672	18,672	18,672
R-squared	0.257	0.273	0.275

Table 7 Mediation mechanism for entrepreneurship.

VARIABLES	(1) lnCitepatent	(2) lnCitepatent
DT_txt	0.230***	0.729***
	(0.0371)	(0.212)
ENT		0.0773***
		(0.00250)
c.DT_txt#c.ENT		0.0440**
		(0.0171)
lnage	−0.142***	−0.124***
	(0.0140)	(0.0137)
soe	0.00551	−0.0170*
	(0.00972)	(0.00949)
lnsize	0.0556***	0.0309***
	(0.00440)	(0.00435)
lnboard	0.151***	0.127***
	(0.0295)	(0.0287)
indp	0.0344	0.00801
	(0.0897)	(0.0874)
top10	−0.0242	0.0197
	(0.0289)	(0.0282)
Lev	−0.0779**	−0.00750
	(0.0319)	(0.0311)
liquid	0.00232	0.00113
	(0.00203)	(0.00197)
ROA	0.634***	0.476***
	(0.0750)	(0.0731)
Constant	−0.728***	0.752***
	(0.121)	(0.126)
Observations	22,200	22,200
R-squared	0.257	0.296

Heterogeneity grouping test for the nature of ownership. In response to the different effects of the nature of enterprise ownership, there are two views. One view holds that the controlling shareholders of non-SOEs are primarily private property rights holders, with market-oriented operations and stronger R&D motivations conducive to breakthrough innovation. The other view holds that SOEs have a close relationship with the government, easy access to compensation and natural credit trust, and possess inherent advantages in terms of technology, which makes them more favorable in terms of innovation. To reveal the differences in enterprise ownership structures, we group enterprises according to whether they are state- or non-state-owned enterprises. The outcomes are presented in Table 8. Among non-SOEs, digital transformation, and entrepreneurship significantly promote disruptive innovation, and the moderator *DT_txt*ENT* coefficient is significant, supporting H1 and H2. Only entrepreneurship is significant among SOEs, and the coefficients of digital transformation and moderator *DT_txt*ENT* are not significant and do not support the hypotheses. The results reveal that although non-SOEs have fewer natural economic and political advantages than do SOEs, this gap has given rise to non-SOE entrepreneurship, significantly stimulating disruptive innovation. The natural advantages of SOEs prevent their entrepreneurship from playing a mediating moderating role in promoting disruptive innovation.

Heterogeneity grouping test for the industry. Considering the different dynamics of digital transformation among firms in different industries, the degree of digital transformation undertaken is influenced by the overall development of the industry, as the economic consequences of such transformation may differ across industries. Compared with manufacturing firms, nonmanufacturing firms are more flexible, enabling them

Table 8 Heterogeneity grouping test for the nature of ownership.

	(1)	(2)
VARIABLES	lnCitepatent	lnCitepatent
DT_txt	0.9396***	0.1762
	(0.2492)	(0.4261)
ENT	0.0664***	0.0963***
	(0.0032)	(0.0041)
c.DT_txt#c.ENT	0.0648***	−0.0113
	(0.0200)	(0.0353)
lnage	−0.0954***	−0.2450***
	(0.0156)	(0.0296)
lnsize	0.0271***	0.0465***
	(0.0057)	(0.0073)
lnboard	0.1474***	0.1165**
	(0.0376)	(0.0460)
indp	0.1394	−0.3271**
	(0.1157)	(0.1380)
top10	0.0456	−0.1293***
	(0.0356)	(0.0495)
Lev	−0.0022	0.0142
	(0.0401)	(0.0520)
liquid	0.0010	0.0031
	(0.0023)	(0.0050)
ROA	0.5570***	0.1791
	(0.0869)	(0.1399)
Constant	0.5163***	1.1764***
	(0.1708)	(0.2047)
Observations	15,021	7175
R-squared	0.2826	0.3536
SOE	0	1

Table 9 Heterogeneity grouping test for the industry.

	(1)	(2)
VARIABLES	lnCitepatent	lnCitepatent
DT_txt	1.0382***	0.1501
	(0.2670)	(0.3361)
ENT	0.0797***	0.0776***
	(0.0052)	(0.0029)
c.DT_txt#c.ENT	0.0660***	−0.0028
	(0.0215)	(0.0272)
lnage	−0.0513**	−0.1471***
	(0.0254)	(0.0161)
soe	−0.0390**	−0.0141
	(0.0172)	(0.0113)
lnsize	0.0172**	0.0345***
	(0.0076)	(0.0052)
lnboard	0.1752***	0.1120***
	(0.0503)	(0.0344)
indp	0.0383	0.0163
	(0.1571)	(0.1037)
top10	0.0977**	−0.0138
	(0.0491)	(0.0340)
Lev	−0.0436	0.0157
	(0.0531)	(0.0377)
liquid	−0.0008	0.0019
	(0.0036)	(0.0023)
ROA	0.2608**	0.6568***
	(0.1253)	(0.0888)
Constant	0.5947***	0.8266***
	(0.2217)	(0.1514)
Observations	5698	16,502
R-squared	0.3177	0.2833
INDUSTRY	0	1

to proactively seek cooperation with external actors, thereby gaining access to a richer set of complementary resources and effectively contributing to disruptive innovation through combined internal and external sources. In this part, the entire sample is divided into manufacturing and nonmanufacturing enterprise groups, and all results are listed in Table 9. The findings reveal that digital transformation facilitates disruptive innovation in nonmanufacturing firms and that entrepreneurship in this industry moderates the relationship between digital transformation and disruptive innovation. In contrast, such a relationship cannot be found in manufacturing firms.

Heterogeneity grouping test for the corporate life cycle. Since the behavioral orientations of enterprises differ across different life cycles, this paper refers to the Dickinson (2011) portfolio cash-flow-based segmentation method, which classifies enterprises into five stages—start-up, growth, maturity, turbulence, and recession—according to net cash flows from operations, financing, and investment, and performs group regressions. Table 10 lists the regression results. The degree of digital transformation of enterprises significantly contributes to disruptive innovation for enterprises in the growth, maturity, turbulence, and recession stages. However, digital transformation in the start-up stage does not drive disruptive innovation. Because, for enterprises in the start-up period, there is a relative lack of talent, capital, and service platforms, digital transformation precisely requires costs and, at this time, cannot promote disruptive innovation. Entrepreneurship plays a mediating role in those enterprises in the growth and decline stages. Digital transformation can coordinate R&D service platforms through entrepreneurship, alleviate the dilemma of there being an insufficient amount of R&D resources and of there being an unclear innovation direction for enterprises in the growth phase, and help enterprises in the growth phase achieve disruptive innovation. For declining enterprises, digital transformation through entrepreneurship can solve the problems of poor internal governance and talent loss, help them realize a "second start-up" stage, bring innovation knowledge overflow and R&D resources to declining enterprises, and promote disruptive innovation.

Research conclusions and implications

This paper empirically discusses how digital transformation influences disruptive innovation and the mechanism at play, using China's listed companies from 2010–2021 as the research object. The findings of this study show that first, overall, digital transformation helps promote disruptive innovation. Second, entrepreneurship positively moderates the effect of digital transformation on the degree of disruptive innovation; i.e., the more significant the entrepreneurship characteristics are, the more digital transformation can play a significant role in promoting disruptive innovation. Finally, regarding differences in firm industry attributes, the mediating effect of entrepreneurship is more evident among private firms, nonmanufacturing companies, and firms in the growth and decline phases.

The findings in this paper have some real implications for businesses to achieve high-quality digital transformation and stimulate disruptive innovation.

First, the digital construction process should be vigorously promoted. Digital transformation execution could efficiently stimulate enterprises' acceleration of their output to promote disruptive innovation results.

Second, companies should focus on the facilitating role of entrepreneurship in achieving disruptive innovation through digital transformation. The entrepreneurial spirit is a vital source of core competitiveness for enterprises. The entrepreneurial spirit

Table 10 Heterogeneity grouping test for the corporate life cycle.

	(1)	(2)	(3)	(4)	(5)
VARIABLES	**lnCitepatent**	**lnCitepatent**	**lnCitepatent**	**lnCitepatent**	**lnCitepatent**
DT_txt	−0.5217	0.9023**	0.7198*	0.9290*	2.2271***
	(0.6639)	(0.3539)	(0.4043)	(0.5084)	(0.8175)
ENT	0.0834***	0.0796***	0.0767***	0.0705***	0.0427***
	(0.0079)	(0.0042)	(0.0044)	(0.0064)	(0.0115)
c.DT_txt#c.ENT	−0.0685	0.0665**	0.0415	0.0568	0.1557**
	(0.0517)	(0.0284)	(0.0336)	(0.0416)	(0.0633)
lnage	−0.0591	−0.1249***	−0.1003***	−0.1945***	−0.1793***
	(0.0410)	(0.0232)	(0.0238)	(0.0363)	(0.0629)
soe	0.0136	−0.0166	−0.0286*	0.0212	0.0205
	(0.0304)	(0.0177)	(0.0157)	(0.0225)	(0.0395)
lnsize	−0.0093	0.0192**	0.0441***	0.0439***	0.0325*
	(0.0148)	(0.0077)	(0.0073)	(0.0107)	(0.0189)
lnboard	−0.0005	0.1501***	0.1868***	0.0264	0.0003
	(0.0922)	(0.0507)	(0.0480)	(0.0692)	(0.1238)
indp	−0.1393	0.1631	−0.0444	−0.1433	0.0609
	(0.2801)	(0.1557)	(0.1451)	(0.2115)	(0.3753)
top10	0.1007	−0.1191**	0.0318	0.0668	0.1217
	(0.0929)	(0.0503)	(0.0474)	(0.0679)	(0.1200)
Lev	0.1921*	−0.0408	−0.0298	−0.0391	−0.2105*
	(0.1009)	(0.0591)	(0.0531)	(0.0699)	(0.1141)
liquid	0.0076	−0.0042	0.0037	0.0063	−0.0076
	(0.0080)	(0.0035)	(0.0032)	(0.0044)	(0.0092)
ROA	0.6676***	0.8317***	0.3725***	0.2831*	0.0499
	(0.2451)	(0.1618)	(0.1206)	(0.1516)	(0.2518)
Constant	1.7659***	1.0725***	0.2521	0.7465**	0.6463
	(0.4128)	(0.2255)	(0.2110)	(0.3130)	(0.5553)
Observations	2756	7565	7855	3037	961
R-squared	0.2532	0.3148	0.3166	0.3142	0.2953
BLC	start-up	growth	maturity	turbulence	recession

plays a crucial role in digital transformation and disruptive innovation. Entrepreneurship should not be underestimated.

Third, the regulating role of entrepreneurship across different enterprises acts heterogeneously according to their development. Therefore, different kinds of enterprises should acknowledge the disparity between their entrepreneurship and other types of enterprises, leverage their strengths, and promote entrepreneurship.

Finally, importantly, this paper has certain limitations. First, the analysis sample is limited to the period 2010–2021, which may restrict the generalizability of the paper's conclusions. Additionally, the measurement of entrepreneurship considers only three indicators, which may not provide a comprehensive understanding of the topic. Therefore, it is necessary to approach our analytical conclusions regarding entrepreneurship with caution. While we identify the stage characteristics of the innovation mechanism in enterprises' digital transformation through the data collected, how to provide a rigorous theoretical explanation remains a significant challenge. Thus, these areas present opportunities for future research.

Data availability

The financial and governance data is from the CSMAR database and everyone can get it from the CSMAR website (https://www.gtarsc.com/) pay-for-access. The textual data is from publicly available sources, and everyone can get it from the JUCHAO website (http://www.cninfo.com.cn/new/index). If readers are interested in replicating this work, they can use crawling software themselves or hire companies to obtain it. We provide the Chinese digitalization word list in Supplementary Information files.

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Notes

1 Digital China Development Report (2021), http://www.cac.gov.cn/2022-08/02/c_1661066515613920.htm.
2 JUCHAO, http://www.cninfo.com.cn/new/commonUrl?url=disclosure/ipo/report.
3 Cntext (1.8.0) library, https://github.com/hidadeng/cntext.

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Author contributions

YW and ZL wrote the full text and revised the text. YW conceptualized and designed the article, literature research, modeling, data analysis, and interpretation. ZL was responsible for literature collection, data collection, analysis and interpretation, and validation of results. All authors agree to be accountable for all aspects of the work.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required as the study did not involve human participants.

Informed consent

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Additional information

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