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The Impact of Population Aging on Digital Economy: A Perspective on Human Capital

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Abstract. As China moves into a stage of deep population aging, demographic transitions are increasingly reshaping patterns of economic development. Drawing on provincial panel data spanning 2013 to 2022, this study employs a panel threshold model to explore the dynamic interactions among aging, digital economy expansion, and human capital accumulation. The results indicate that, in general, population aging exerts a dampening effect on digital economic growth. However, the extent of this impact is contingent upon the level of human capital: inadequate human capital significantly constrains digital progress, while higher levels of human capital can offset demographic pressures and even foster digital development. Moreover, notable regional disparities emerge. In the eastern provinces, the effect of aging on digitalization is statistically insignificant, whereas in the central, western, and northeastern regions, aging generates pronounced negative consequences. These findings suggest that to mitigate demographic challenges and harness the opportunities of an aging society, it is essential to integrate the "silver economy" with digital transformation, enhance digital literacy and adaptability among older populations, and address regional imbalances in digital economy advancement, thereby promoting more coordinated and inclusive growth.

Keywords: Digital Economy, Population Aging, Human Capital, Threshold Model

1. Introduction

With continuous technological advancement and rising life expectancy, population aging has emerged as a critical factor shaping socioeconomic development. According to data released by the National Bureau of Statistics, by the end of 2024, China's population aged 60 and above had reached 310 million, accounting for 22% of the total, while those aged 65 and over numbered 220 million, or 15.6%. These figures confirm that China has entered a stage of profound aging, and international evidence shows that such demographic shifts often impose lasting challenges on economic dynamism and social governance. At the same time, the digital economy—an outcome of the new technological revolution—has become a driving force for high-quality growth. Since the 18th National Congress of the Communist Party of China, the digital sector has expanded rapidly, increasing from 11 trillion yuan in 2012 to an expected 50 trillion yuan by the end of 2025, maintaining its position as the world's second largest. Infrastructure development has also advanced significantly: by mid-2025, China had installed 4.55 million 5G base stations and registered more

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than 220 million gigabit broadband users; by the end of 2024, the nation's total computing power reached 280 EFLOPS, with intelligent computing accounting for about one-third and projected to grow by more than 40% in 2025. These achievements provide a solid foundation for the sustained expansion of the digital economy.

In this context of rapid digitalization, human capital plays an increasingly pivotal role. Unlike traditional growth models that rely heavily on labor quantity and basic skills, the digital economy demands workers with advanced technical expertise, innovative capacity, and strong information literacy. This raises new requirements for human capital accumulation, structural upgrading, and lifelong education systems. However, accelerating population aging may weaken the vitality of the labor force and impose constraints on digital transformation. Against this backdrop, investigating how aging influences the digital economy is of both theoretical and practical importance. This paper, adopting a human capital perspective, systematically examines the interaction between demographic aging and digital development, expands the explanatory framework of digital economy research, and offers policy recommendations for promoting digital transformation under demographic pressure. The study also provides fresh empirical evidence for the integration of aging and human capital theories.

2. Literature review

With the advancement of science and technology and the progression of the Industry 4.0 era, the digital economy has emerged as a transformative force, accelerating industrial restructuring and economic upgrading. Since the beginning of the 21st century, China has actively fostered digital industries as part of its broader strategy to move beyond labor-intensive manufacturing toward high value-added and intelligent production models. In this transition, the digital economy not only serves as a vital engine for industrial upgrading but also represents a strategic response to the pressures of globalization and rapid technological change.

Existing scholarship on the digital economy has become increasingly comprehensive in recent years, encompassing both theoretical and empirical approaches. On the theoretical front, researchers have conceptualized the digital economy from a macro perspective, highlighting its implications for industrial organization, labor relations, and business models. For instance, Mohd Javaid et al. argue that the digital economy enhances production efficiency, increases industrial value creation, strengthens managerial oversight, and fosters entirely new forms of industries and markets [1]. Empirically, scholars have focused on the mechanisms and heterogeneous effects of digital transformation. Xu and Li, using provincial panel data from 2013 to 2019, identify nonlinear effects of urbanization and industrial structure on the digital economy [2]. Similarly, Zhu et al. find that digitalization influences employment structures differently depending on region, marketization levels, and industrial composition [3]. In the Chinese context, Cheng and Wang further emphasize the role of political variables, showing that local officials' educational backgrounds shape the outcomes of digital economy development [4].

Parallel to these trends, population aging has become a structural constraint on economic development as living standards rise. Aging not only reduces labor supply and participation rates but also reshapes consumption preferences, saving behavior, and pressures on social security systems. Prior studies highlight the multidimensional impacts of aging: on the one hand, shrinking labor supply calls for reforms in pension and social security systems [5]; on the other hand, Ngoc and Tran's research on Vietnam indicates that older populations exhibit more conservative consumption patterns, which dampens consumption upgrading and investment incentives. Rising expenditures on pensions and healthcare also intensify fiscal burdens, crowding out other policy priorities. Regional

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disparities exacerbate these challenges, as less competitive areas, such as remote rural regions, require more policy support to cope with aging [6].

Although research on the digital economy and population aging is abundant when studied separately, integrated analyses remain relatively scarce. Most existing works approach the subject from either theoretical perspectives or empirical models that explore the constraints aging imposes on digital development. For example, Wang highlights the regional heterogeneity of this effect, noting that the inhibitory role of aging is particularly strong in western provinces [7]; By employing panel data from 2012 to 2020, Bi shows that aging affects the digital economy through innovation as a mediating channel, revealing how demographic change weakens innovation capacity [8]; Han, from a distributional perspective, investigates the indirect effects of aging on economic growth and emphasizes that policies such as delayed retirement and expanding labor supply can mitigate negative demographic shocks [9]. At the policy level, Che Ning argues that the digital economy itself can be leveraged as a tool to address aging challenges, through innovations such as smart elderly care, telemedicine, and digital literacy training for older cohorts [10].

Against this background, this paper adopts a human capital perspective and applies a panel threshold model to analyze the mechanisms through which population aging affects digital economic development, with special attention to regional heterogeneity. The study seeks to enrich the theoretical framework of how demographic transitions interact with digital transformation and to provide policy insights for sustaining digital economy growth in an aging society.

3. Theoretical model and research hypotheses

According to life-cycle theory, consumer behavior is closely linked to age. Younger cohorts are generally more receptive to novel products and services, show a higher degree of digital adoption in their daily lives, and demonstrate strong preferences for digital consumption. In contrast, older groups are more constrained by established consumption habits and lower adaptability to new technologies, making them more inclined toward traditional services. As the aging process deepens, such divergence in consumption patterns directly reshapes social demand. The conservative consumption orientation of older populations increases reliance on conventional services, thereby narrowing the potential market for the digital economy, reducing demand for digital goods and services, and leading to a relative shift toward non-digital consumption. Hence, this study proposes the following hypothesis:

H1: Population aging exerts a negative impact on the development of the digital economy.

Building on Romer's endogenous growth theory, technological progress and human capital accumulation are identified as key drivers of economic growth. Both dimensions are essential for the digital economy: technology fuels innovation and iterative upgrades of digital tools, while human capital enhances workers' knowledge and skill levels. Aging, however, may suppress digital economic growth by reducing the working-age population, weakening incentives for research and development, and dampening overall demand. Nonetheless, when human capital is sufficiently strong, higher educational attainment and advanced skills can improve innovation efficiency, partially offsetting the negative demographic effect. Accordingly, the second hypothesis is proposed:

H2: The effect of aging on the digital economy is nonlinear, varying with the level of human capital.

The theory of regional development gradients suggests that economic growth across regions is highly uneven, driven by differences in factor endowments, industrial structures, capital intensity, technological capabilities, and labor quality. In China, both aging and digital economy development exhibit pronounced regional disparities. In the eastern provinces, a large proportion of the resident

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population consists of younger migrant workers, providing critical labor support for digital industries; however, the registered population is more aged, influencing local human capital accumulation and consumption demand. In contrast, non-eastern regions often face challenges of "hollowed-out" cities and rural areas characterized by severe labor outflows, leaving behind a highly aged demographic structure. These distinct patterns form a sharp contrast with the eastern region. Based on such disparities, this study proposes the third hypothesis:

H3: The impact of population aging on the digital economy is likely to be heterogeneous across regions.

4. Model setting and description of variables

4.1. Research design

To examine the impact of population aging on the digital economy, and following the approach of relevant scholars, this study constructs a fixed-effects model incorporating both digital economic development and population aging:

$$digeco_{it} = \beta_0 + \beta_1 olddep_{it} + \theta X_{it} + P_i + Y_t + \varepsilon_{it} \tag{1}$$

In Model (1), i denotes provinces and t represents years. $digeco_{it}$ is the level of digital economic development, while $olddep_{it}$ measures population aging. X_{it} includes a set of control variables, namely government policy actions (gov_{it}), technological innovation ($tech_{it}$), and industrial structure ($stru_{it}$). P_i captures province-specific fixed effects, Y_t accounts for time fixed effects, and ε_{it} is the error term.

Considering that the effect of population aging on the digital economy may vary across different levels of human capital, a threshold-effect model is further constructed, where I is an indicator function taking values of 0 or 1, and γ denotes the threshold value.

$$digeco_{it} = \beta_0 + \beta_1 olddep_{it} * I(human_{it} \le \gamma_1) + \beta_2 olddep_{it} * I(human_{it} > \gamma_1) + \theta X_{it} + P_i + Y_t + \varepsilon_{it} \tag{2}$$

4.2. Variable selection

The dependent variable in this study is the level of digital economic development. Following the approach of Liu et al. [11], it is measured across three dimensions: informatization, internet development, and digital transaction activity. Based on data availability, the total telecom services per capita is used to capture the level of informatization; internet broadband penetration and the proportion of employees in the information software industry are adopted as indicators of internet development; and the share of enterprises engaged in e-commerce transactions serves as a measure of digital transaction activity. In addition, following Zhao et al. [12], the Peking University Digital Inclusive Finance Index is incorporated to account for digital financial development.

The core explanatory variable is the level of population aging ($olddep_{it}$), measured by the old-age dependency ratio of individuals aged 65 and above. The threshold variable is human capital ($human_{it}$), proxied by the number of students enrolled in regular higher education institutions (in tens of millions).

To more accurately assess the impact of population aging on digital economic development, a set of control variables that may influence digital economic outcomes are included. For government

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policy actions (gov_{it}), the ratio of fiscal expenditure to GDP is used; for technological innovation ($tech_{it}$), the number of patent grants per 10,000 people is employed; and for industrial structure ($stru_{it}$), the ratio of tertiary to secondary industry output is selected.

4.3. Data source and descriptive statistics

The sample comprises 31 provinces in mainland China (excluding Hong Kong, Macao, and Taiwan) over the period 2013–2022. Data are primarily drawn from the China Statistical Yearbook, the National Bureau of Statistics, and official World Bank sources. Descriptive statistics for all variables are presented in Table 1.

Table 1. Descriptive statistics of variables (N=310)

Variable	Mean	Std. Dev.	Min	Max
digeco	0.212	0.145	0.021	0.918
olddep	16.062	4.568	7.010	28.770
gov	3.235	0.472	2.351	4.908
tech	15.285	17.328	0.382	92.821
stru	1.372	0.739	0.632	5.297
human	0.095	0.060	0.003	0.282

5. Analysis of empirical results

5.1. Benchmark regression

The baseline regression results are presented in Table 2. Columns (1) through (4) display the estimated effects of population aging on digital economic development as control variables are progressively introduced. Model (1) includes only the core explanatory variable—population aging—while Models (2) to (4) incorporate additional controls sequentially. The results indicate that the coefficient for population aging is significantly negative, suggesting that an increase in aging levels substantially inhibits digital economic growth. Specifically, a one-unit rise in population aging corresponds to an average decrease of 0.004 units in digital economy development, supporting Hypothesis 1.

Further examination of the control variables reveals their distinct impacts on the dependent variable. Scientific research and innovation capacity, along with optimization of industrial structure, exert a strong positive influence on digital economic development. Upgrading the industrial structure facilitates the emergence of new business models and innovative environments, thereby creating favorable conditions for the digital economy. Conversely, excessive government expenditure may crowd out funding for research and other innovation-related activities, potentially constraining digital economic growth.

Table 2. Regression results (N=310)

Variable	digeco			
	(1)	(2)	(3)	(4)
olddep	-0.003**	-0.003*	-0.003**	-0.004**
	(0.002)	(0.002)	(0.002)	(0.001)

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Table 2. (continued)

gov		-0.058**	-0.064***	-0.075***
		(0.028)	(0.024)	(0.026)
tech			0.002***	0.001***
			(0.001)	(0.000)
stru				0.042**
				(0.020)
Constant	0.445***	0.614***	0.559***	0.434***
	(0.021)	(0.087)	(0.073)	(0.094)
Province, time fixed		Yes		
R^2	0.962	0.963	0.968	0.970

Note: Robust standard errors are in parentheses; ***, **, and * denote significance levels of 1%, 5%, and 10%, respectively, as in the table below.

5.2. Robustness test analysis

To further verify the robustness of the findings, this study conducts three types of robustness checks: excluding municipalities, adding control variables, and applying winsorization, with the results presented in Table 3. (1) Municipalities generally exhibit higher levels of economic development and serve as national hubs in economic, political, and technological domains, attracting greater talent, advanced technologies, and policy benefits. Consequently, their digital economy development and aging levels systematically differ from other provinces. To account for this, the analysis excludes municipalities in one robustness test. (2) As China's open economy evolves and the dual circulation strategy—emphasizing domestic circulation while integrating with international circulation—guides economic development, the degree of openness becomes a critical factor influencing the digital economy. In this study, trade dependence (r_trade) is introduced as an additional control variable in the model to capture this effect. (3) Considering the potential presence of outliers or extreme values that may bias regression results, key variables are winsorized at the 1% and 99% quantiles. This procedure mitigates the influence of extreme observations and enhances the reliability and interpretability of the model. Across all three robustness checks, the negative impact of population aging on digital economic development remains statistically significant, confirming the stability and robustness of the study's findings.

Table 3. Robustness test results

Variable	(1)	(2)	(3)
	Excluding municipality samples	Adding control variable	Winsorizing
olddep	-0.004***(0.001)	-0.003**(0.001)	-0.003*(0.001)
gov	0.001*(0.000)	0.001***(0.000)	0.001***(0.000)
tech	-0.045(0.030)	-0.087***(0.025)	-0.056**(0.020)
stru	0.006(0.013)	0.044**(0.017)	0.018*(0.010)
r_trade		-0.077**(0.031)	
Constant	0.243**(0.095)	0.356***(0.077)	0.258***(0.072)
Province, time fixed		Yes	

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Table 3. (continued)

N	270	310	310
R^2	0.970	0.971	0.964

5.3. Threshold effect test

This study selects the level of human capital as the threshold variable. The results in Table 4 indicate that the single-threshold test is significant, whereas the double- and triple-threshold tests are not. As shown in Table 5, when the human capital level is below 0.004, population aging exerts a significant negative effect on digital economic development; conversely, when human capital exceeds 0.004, the effect becomes significantly positive, supporting Hypothesis 2. This pattern may be explained by the fact that at lower levels of human capital, the workforce lacks sufficient education and skills, causing aging to exacerbate labor shortages, reduce innovation capacity, and amplify structural inefficiencies, thereby restraining the growth of the digital economy. In contrast, at higher human capital levels, accumulated education and skills can effectively offset the adverse effects of aging. The older population may complement a highly skilled workforce through knowledge and experience transfer, facilitating technological application and industrial upgrading, and thereby promoting digital economic expansion. Hence, human capital plays a critical threshold-regulating role in the relationship between population aging and digital economy development.

Table 4. Results of threshold effect test

Threshold Variable	Model	Threshold	F-value	P-value
Tech	single	0.004	18.94	0.040
	double	0.023	16.46	0.193
	triple	0.076	14.21	0.613

Table 5. Threshold effect results

Variable	digeco
$olddep \times I(human \leq \gamma_1)$	-0.023***(0.008)
$olddep \times I(\text{human} > \gamma_1)$	0.008***(0.003)
Controls	Yes
Constant	-0.721***(0.216)
γ_1	0.004
N	310
R^2	0.559

5.4. Heterogeneity analysis

This study further categorizes the 31 surveyed provinces into two groups: eastern and non-eastern regions, conducting a heterogeneity analysis from a regional perspective. The results of this test are presented in Table 6. The findings indicate that aging in eastern provinces does not exert a significant impact on the development of the digital economy, whereas in non-eastern regions,

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higher levels of population aging significantly inhibit digital economic growth, confirming Hypothesis 3. This discrepancy may be attributed to the relatively advanced economic development in the eastern region, which creates a noticeable "talent siphoning" effect, alleviating labor structure pressures caused by demographic aging and supporting deeper development of digital industries. Moreover, the older population in eastern provinces generally has a higher educational attainment, making them more receptive to novel digital products and services, while their stronger purchasing power provides additional demand-side support. Coupled with the more mature overall development of the digital economy and stronger policy support in the east, these factors collectively mitigate the negative effects of aging on digital economic expansion.

Table 6. Heterogeneity analysis

Variable	(1)	(2)
	Eastern	Non-eastern
olddep	-0.001(0.002)	-0.004**(0.002)
gov	0.001***(0.000)	0.001***(0.000)
tech	-0.052(0.040)	-0.075***(0.026)
stru	0.067***(0.017)	0.038*(0.021)
Constant	0.159(0.120)	0.316***(0.083)
Province, time fixed	Yes	
N	100	250
R^2	0.977	0.971

6. Conclusion and recommendation

6.1. Conclusion

Drawing on provincial panel data from China spanning 2013–2022, this study investigates the dynamic interplay among population aging, digital economy expansion, and human capital accumulation. The main findings can be summarized as follows: (1) overall, population aging exerts a constraining effect on the development of the digital economy; (2) when human capital reserves are insufficient, aging significantly hampers digitalization, whereas under higher levels of human capital, it shows a facilitating effect; (3) regional heterogeneity is pronounced, with aging exerting no significant influence on the digital economy in the eastern provinces, while producing a strong negative impact in the central, western, and northeastern regions.

6.2. Recommendation

Based on these results, three policy recommendations are advanced. First, promote the integration of the digital economy with the "silver economy." In the context of rapid aging, greater application of digital technologies should be encouraged in healthcare, elderly care, and related services, while public services and e-commerce platforms could be adapted with user-friendly functions such as large-font modes and senior-centered designs to lower access barriers. Industrial convergence can not only meet the growing needs of older cohorts but also transform demographic pressures into a new driver of digital growth. Second, address the restraining effect of aging through investment in education and training. Expanding digital skill programs for middle-aged and elderly groups,

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building institutions such as universities for seniors, and strengthening lifelong learning mechanisms would enhance the digital adaptability of human capital. At the same time, policies for attracting external digital talent should be introduced to offset the adverse impact of aging. Enhancing digital literacy across society will increase the overall human capital stock and mitigate demographic headwinds. Third, implement regionally differentiated strategies. The developed eastern region should act as a demonstration zone, advancing the digital economy through greater R&D investment and providing technological spillovers to less developed areas. Other regions should develop context-specific initiatives, such as promoting rural digital commerce in the east and central provinces, or building computing power hubs in the west. In parallel, education and training for the labor force should be strengthened to improve digital capabilities, thereby alleviating the dual challenges of aging and rural population outflow. Such measures can foster coordinated regional development of the digital economy.

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