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Hardware is not enough: unpacking the configurational synergy of person-environment fit in graduate digital literacy

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Abstract

This study examines how digital literacy among graduate students in the social sciences emerges from different configurations of environmental conditions and individual motivation. Drawing on person–environment fit (PEF) theory, it uses a sequential mixed-methods design combining the Delphi method, entropy weighting, necessary condition analysis (NCA), and fuzzy-set qualitative comparative analysis (fsQCA) to analyze survey data from 640 graduate students across 30 provinces in China. The results show that interest drive and household digital support attitude are necessary but not sufficient conditions for high digital literacy. The fsQCA findings further reveal three distinct pathways to high digital literacy: an interest–curriculum synergy path, an independent-practice-dominant path, and a self-growth–practice synergy path. In contrast, low independent practice drive and low curriculum adaptability emerge as key constraints associated with non-high digital literacy. These findings suggest that digital literacy development cannot be explained by resource provision alone, but depends on the configurational alignment of technological resources, curriculum support, and learner motivation.

Keywords Digital Literacy · PEF Theory · Scale Development · Configuration Analysis

Introduction

Digital literacy has become a strategic capability in an era of rapid global digital transformation. China has incorporated "educational digitalization" into its national strategy, emphasizing the enhancement of national digital literacy through "new infrastructure" and "educational informatization." Internationally, the EU's Digital Education Action Plan (2021-2027) also designates digital literacy as a core goal of educational modernization, with its DigComp framework now covering 27 member states. Against this backdrop, the development of digital competence has attracted growing scholarly attention (Alfalah et al., 2025; Ching, 2025; Meng et al., 2025; Son & Ha, 2025).

Since the launch of new educational infrastructure in 2021, China's Ministry of Education's Three-Year Effectiveness Review of the Educational Digitalization Strategic Action shows that by the end of 2024, 43,000 smart classrooms and training rooms had been built nationwide. However, investment in digital infrastructure has not always translated into effective use. Latest monitoring indicates that equipment utilization rates in underdeveloped regions remain generally low, with excess bandwidth often going underused, resulting in resource waste characterized by "high input and low efficiency" (OECD, 2023). According to data from iResearch's Smart Campus Equipment Survey 2024, the utilization rate of smart classrooms in colleges and universities is only 35%-50%, and more than 60% of students report that the systems are difficult to use and technical support is slow. These patterns suggest that hardware provision alone cannot improve digital literacy unless it is accompanied by effective institutional support and sustained learner motivation. Problems in the soft environment are especially visible: in learning and daily life applications, services such as course selection, fee payment, and library borrowing remain fragmented and poorly integrated (Aničić et al., 2023). According to the 2023 survey data from the Digital Center of Fudan University, students need to log into an average of 4.2 platforms to complete daily tasks, which increases the time required to complete routine tasks by 47%. A 2024 survey by China's Educational Informatization Network further indicates that inadequate curriculum support, weak data literacy among teachers, and underdeveloped on-campus data governance have become key bottlenecks preventing students from turning technological resources into meaningful learning, research, and innovation outcomes. Without this kind of institutional and pedagogical support, additional technology may even increase students' cognitive burden. Thus, simply relying on hardware investment cannot fundamentally solve the problem of cultivating digital literacy among university students. What is needed, therefore, is not further hardware expansion alone, but closer alignment among infrastructure, institutional support, and, where relevant, family-level support.

In response to these practical issues and the academic debate over "hardware priority or software-hardware synergy" in cultivating university students' digital literacy, prior studies have approached this issue from several directions. These include the relationship between digital infrastructure investment and educational effectiveness (Derder et al., 2024), the supporting role of soft environmental conditions in digital literacy (Asmayawati, 2023; Yu et al., 2024), and the driving mechanism of individual motivation on learning outcomes (Law et al., 2017; Vaszkun & Szakács, 2025). Bringing technological resources, the broader learning environment, and learner motivation into a common analytical framework is therefore important for understanding both their joint effects and the multiple pathways through which digital literacy develops. However, due to the limitations of traditional linear analysis methods, existing studies mostly focus on single dimensions or two-factor combinations, making it difficult to identify the equivalence of different condition combinations in enhancing digital literacy (Geremew et al., 2024; Sarstedt et al., 2024). Yet digital literacy development is inherently configurational: it emerges from the interaction between external environments and internal dispositions rather than from any single factor in isolation. Current research still provides limited insight into how multiple conditions work together, how different combinations may produce the same outcome, and how such pathways vary across contexts. Nor has prior research developed a sufficiently integrated framework for assessing how different combinations of hard and soft conditions shape digital literacy outcomes.

Addressing these gaps, this study examines digital literacy among graduate students in the social sciences in China through the lens of person–environment fit (PEF) theory and a configurational approach. It asks two questions. First, are there threshold levels of particular conditions for high digital literacy? Second, can high digital literacy be achieved through multiple distinct combinations of technological resources, the broader learning environment, and learner motivation? By addressing these questions, the study clarifies how different combinations of conditions shape digital literacy.

Literature review and analytical frameworks

Research on differentiated cultivation pathways of digital literacy has focused on three main dimensions in existing literature: the dimension of environmental hard conditions, the dimension of environmental soft conditions, and the dimension of individual intrinsic motivation. The theoretical basis of these three dimensions originates from the PEF theory, first proposed by Frank Parsons in 1909 and later extended into organizational and educational research by Murray and Lewin. The following will systematically elaborate on the differentiated logics and correlations of these three

theoretical perspectives in explaining the cultivation of digital literacy among graduate students in the social sciences.

Dimension of environmental hard conditions. Environmental hard conditions refer to the physical and technical infrastructure supporting the cultivation of digital literacy, whose theoretical basis can be traced back to the Technology Acceptance Model (Davis et al., 1989) and the Resource-Based View (Barney, 1991).

Existing studies focus on two core issues: first, the balance of resource allocation and functional adaptability. Research on regional differences shows that the equipment coverage rate in colleges and universities in central and western regions is significantly lower than that in eastern regions (Hu, 2023). There is a debate on the priority of resource allocation between "hardware priority" (Falch, 2022) and "software-hardware synergy" (Li et al., 2021; Wang et al., 2024). Studies on the adaptability of technical platforms present a polarized situation: supporters of the TPACK framework emphasize discipline integration, advocating the in-depth interaction of technological knowledge, subject content knowledge, and pedagogical knowledge; opponents warn that the complexity of information technology raises the threshold for use (Chouki et al., 2020). Second, spatial reconstruction and effectiveness evaluation. "Cloud classrooms" have significantly improved students' academic performance (Ahmed et al., 2025), but purely virtual environments have a significant negative impact on the perceptual level of skill learning (Chang, 2021). There is a contradiction between "short-term equipment indicators" and "long-term capability indicators" in effectiveness evaluation standards (Petko et al., 2017). Science and engineering disciplines emphasize the advancement of equipment, while the humanities and social sciences pay more attention to the richness of resources (Li et al., 2025).

Dimension of environmental soft conditions. Environmental soft conditions refer to the non-material support system in the cultivation of digital literacy, covering elements such as institutional design, cultural atmosphere, and interactive relationships. Its theoretical roots can be traced back to social cognitive theory (Bandura, 1986) and institutional isomorphism theory (DiMaggio & Powell, 1983). The European Digital Competence Framework emphasises the importance of an enabling environment for digital competence development (Vuorikari et al., 2022). Although China's Action Plan for Improving National Digital Literacy and Skills proposed soft indicators such as "digital ethics" and "digital security," the implementation path is still vague.

Studies on institutional support mechanisms show significant differentiation. The EU's Digital Education at School in Europe requires member states to systematically evaluate the offering of digital courses in schools, teachers' digital teaching capabilities, and students' digital literacy levels. However, in the practice of Chinese colleges and

universities, the contradiction between administrative orders and teachers' autonomy is prominent: studies have shown that some colleges and universities find it difficult to effectively promote teachers' participation due to the lack of internal policies for Open Educational Resources (OER) and Open Educational Practices (OEP); while in colleges and universities that provide incentive measures such as bonus funding and include contributions to open educational resources in academic promotion standards, teachers' participation is significantly improved (Huang et al., 2020). This difference reveals the practical conflict between institutional rigidity and flexible adaptation. Latest studies have confirmed that the integration of digital tools with traditional teaching methods can significantly improve acceptance (Hattami, 2025).

The controversies among academic schools focus on two pairs of contradictions: first, the institutional rigidity school vs. the flexible adaptation school. The former advocates that unified standards are the premise of fairness (Zhang, 2024), while the latter emphasizes independent adaptation of colleges and universities (Kerssens & Dijck, 2022; Kollerup et al., 2025). Second, structured interaction vs. free exploration. Supporters of structured interaction advocate capability certification systems (Buchan et al., 2024; Wong et al., 2023), while advocates of free exploration promote borderless communities (Jung & Lee, 2022; Li et al., 2025).

The above deep-seated contradictions stem from conflicts in multiple dimensions: differences in goals between developing and developed countries in terms of inclusiveness and innovation, differences in the adaptability of educational traditions to interactive teaching, and intergenerational cognitive gaps. These multi-dimensional conflicts highlight that the cultivation path of digital literacy urgently needs to shift from a single-dimensional design to systematic reconstruction and multi-dimensional synergy.

Dimension of individual intrinsic motivation. Individual intrinsic motivation refers to the internal psychological motivation system for learners to actively develop digital literacy, whose theoretical roots can be traced back to self-determination theory (Deci & Ryan, 1985) and social cognitive career theory (Lent et al., 1994). A study by Vaszkun & Szakács (2025) found that internal drive has a significantly higher explanatory power for online learning effectiveness than environmental factors. The EU's DigComp framework deconstructs it into three dimensions: "cognitive ability," "motivational tendency," and "meta-learning strategies." China's Work Points for Improving National Digital Literacy and Skills in 2024 emphasizes the core role of "digital identity," revealing the paradigmatic differences between Eastern and Western theoretical constructions.

The academic community has fundamental differences on the plasticity of digital cognitive ability. On the one hand, the use of digital devices has been proven to be

related to brain plasticity, which will affect academic performance and cognitive development (Clemente et al., 2024); on the other hand, excessive use of digital technology may damage comprehension and decision-making abilities, thus challenging the view that digital activities generally promote beneficial plasticity (Barros et al., 2024). Regarding the dual paths driven by motivation, self-determination theory distinguishes between external regulation and intrinsic motivation. Those dominated by intrinsic motivation have longer learning persistence than those with external regulation (Vaszkun & Szakács, 2025), but there are paradigmatic conflicts in incentive design. Regarding the effectiveness differentiation of meta-learning strategies, meta-cognitive monitoring ability has been proven to be a key variable in predicting the development speed of digital literacy (Lin et al., 2024). Students with stronger language skills, more meta-cognitive skills, and more internet experience are more likely to correctly answer comprehension questions (Burin et al., 2020).

Existing studies have made significant progress in the three dimensions of digital literacy cultivation, providing key theoretical fulcrums for constructing a digital literacy cultivation system based on "person-environment" fit. However, there are still several limitations that need to be addressed. The cultivation of digital literacy is essentially a complex process of multi-factor synergy, and single-dimensional analysis is difficult to reveal its internal mechanism. Therefore, it is urgent to shift from "single-dimensional capability building" to "multi-dimensional dynamic system reconstruction" to fully grasp the interaction logic between the environment and individuals. In this context, the use of configurational analysis methods is of great significance: by deconstructing the dynamic coupling paths between environment and individuals from a holistic perspective, it can not only identify the key mechanisms of digital literacy cultivation under different conditions but also provide a solid theoretical basis for the formulation of differentiated cultivation strategies.

Analytical frameworks. This study constructs a configurational model based on Person-Environment Fit theory, delineating the core dimensions and causal conditions for cultivating digital literacy. Through a systematic review of literature and theoretical frameworks, this study establishes that the cultivation of digital literacy needs to focus on the three dimensions of "person-environment" fit: environmental hard conditions → environmental soft conditions → individual intrinsic motivation. This progressive relationship indicates that the development of digital literacy first relies on the support of physical facilities and technical resources, then requires the synergistic support of institutional design and cultural atmosphere, and further realizes the internalization of literacy through the active response of learners. Based on this theoretical framework and combined with the practical needs of the research question, this study finally extracts seven causal conditions from the three dimensions: digital infrastructure

support, household digital resource supply (environmental hard conditions dimension); curriculum adaptability, household digital support attitude (environmental soft conditions dimension); self-growth drive, interest drive, and independent practice drive (individual intrinsic motivation dimension). The theoretical model framework and configurational model are shown in Fig. 1.

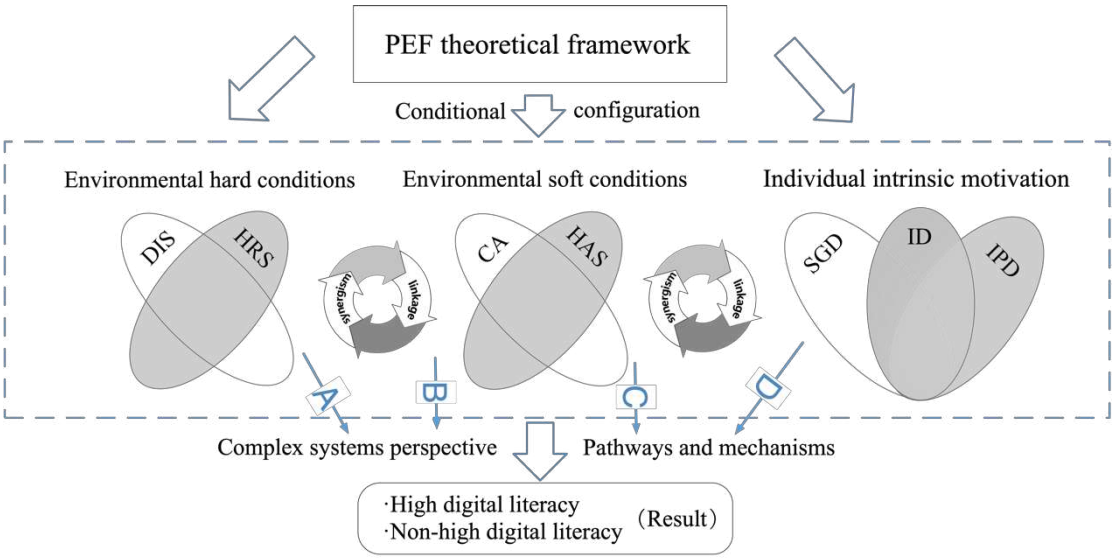


Fig. 1 Complex driving patterns for digital literacy.

Note: A, B, and C denote the impacts of environmental hard conditions, environmental soft conditions, and individual intrinsic motivation on digital literacy, respectively; D represents their combined effect on digital literacy.

Research methodology

Instrument. Data were gathered using a questionnaire partitioned into three parts. The first part collects basic statistical information about the respondents. The second part assessed the seven causal conditions. The third part consists of the digital literacy scale, which was rigorously developed through the Delphi method described in the following section. The final scale comprises 20 items across five dimensions: digital thinking and cognition, digital collaboration and communication, digital application and operation, digital creativity and problem-solving, and digital ethics and security. Items were measured on a 5-point Likert scale (1=strongly disagree, 5=strongly agree).

Data collection and sample. The nationwide questionnaire survey was conducted via the Wenjuanxing platform, a widely used online survey platform in China, from July to August, 2025. Before the data collection, all participants were informed about the objectives of the study, the voluntary nature of their participation, and the confidentiality of their responses. Written informed consent was obtained from all participants before they proceeded to complete the questionnaire. The sampling design

emphasized both breadth and representativeness, covering 30 provinces, autonomous regions, and municipalities across China to ensure balanced geographic distribution and contextual diversity. Respondents were graduate students in the social sciences from various types of universities—including comprehensive, engineering, science, normal, and finance and economics institutions. The sample encompassed academic and professional master's as well as doctoral students, ensuring broad coverage across graduate training levels in the social sciences. This design produced a diverse sample in terms of background and academic level. After data collection, a multi-step quality screening process was conducted. A total of 689 responses were initially obtained. Following the removal of responses with a completion time of less than 60 seconds, uniform response patterns, and internally inconsistent answers, 640 cases were retained for analysis, resulting in an effective response rate of 92.89%.

Research methods. To rigorously capture the multidimensional nature of digital literacy, this study employs a staged mixed-methods research design, combining Delphi analysis, entropy weighting, Necessary Condition Analysis (NCA), and fuzzy-set Qualitative Comparative Analysis (fsQCA).

The study begins with the Delphi method, which enables theory-informed construction of a digital literacy scale rather than merely adapting existing instruments. Given the conceptual ambiguity of digital literacy, expert consensus was essential. Drawing from core literature (Ackermans et al., 2024; Blank & Schmidt, 2022; Fan & Li, 2025; Guillén et al., 2023; Pedaste et al., 2023; Vaszkun & Szakács, 2025), five dimensions were delineated. Two iterative consultation rounds were conducted with a panel of five experts (two professors, one government official, and two industry practitioners). Following two rounds of Delphi consultation, the scale was refined through item addition, deletion, and wording revision. Seven items were added, seven items with $CV > 0.25$ were excluded, and several item formulations were further revised and reorganized, ensuring the scale's semantic clarity and theoretical coherence before the formal survey.

Following scale construction, the entropy method was used to determine indicator weights and produce composite digital literacy scores. Unlike subjective weighting approaches—which may inadvertently privilege theoretically favored dimensions—the entropy method leverages variation embedded in empirical data. Through normalization, probabilistic transformation, entropy computation, and weight derivation, it provides an objective weighting architecture that is particularly suitable for complex constructs involving multiple interdependent dimensions.

Subsequently, NCA and fsQCA are combined to uncover both necessary conditions and sufficient causal pathways. NCA identifies whether specific dimensions must reach a threshold before high digital literacy can emerge, illuminating structural

constraints that cannot be compensated for by other factors (Dul et al., 2020). In contrast, fsQCA examines equifinal configurations of causal conditions, acknowledging that multiple distinct pathways may lead to the same high-level outcome (Misangyi et al., 2017). Whereas NCA reveals "must-have" conditions, fsQCA uncovers "how-possible" patterns—together offering a nuanced, asymmetric view of causality.

Variable measurement. In this study, digital literacy serves as the outcome variable and is measured using a self-developed five-point Likert scale, with a comprehensive assessment further conducted by combining the Delphi method and the entropy weighting approach. Instead of treating digital literacy as a monolithic construct, the measurement approach reflects its layered nature and enables variance-sensitive quantification across multiple dimensions.

The selection of causal conditions is grounded in PEF theory, which conceptualizes digital literacy as an emergent property shaped by the interplay between environmental hard conditions, environmental soft conditions, and individual intrinsic motivation. Environmental hard conditions denote tangible technological infrastructures—for example, access to devices, network capacity, and learning platforms. Environmental soft conditions, in contrast, refer to socio-cultural and relational support from educational and familial environments, including the quality of curriculum design and attitudinal support toward digital learning. Individual intrinsic motivation captures internal drivers that sustain autonomous learning behavior. Within this theoretical architecture, digital literacy advances not merely through resource enrichment but through a dynamic alignment between external environmental inputs and individual learning incentives.

Based on this theoretical framework and tailored to the context of social science graduate education, the three dimensions are operationalized into measurable indicators (see Table 1). The environmental hard conditions include "digital infrastructure support" (*DIS*) and "household digital resource supply" (*HRS*); the environmental soft conditions include "curriculum adaptability" (*CA*) and "household digital support attitude" (*HAS*); and the individual intrinsic motivation includes "self-growth drive" (*SGD*), "interest drive" (*ID*), and "independent practice drive" (*IPD*). All seven causal conditions were operationalized through self-reported questionnaire items rated on a five-point Likert scale (1=strongly disagree, 5=strongly agree). Appendix 1 presents the measurement items for the causal conditions and the 20-item digital literacy scale (outcome variable). To ensure measurement quality, reliability, and validity analyses were conducted on the 20-item digital literacy scale (Cronbach's alpha = 0.92; subscales 0.755-0.866; KMO > 0.7; cumulative variance explained > 60%).

Table 1 Outcome and causal conditions.

Variables	Code	Description
Digital literacy	*DL*	Measured using the Delphi method and the entropy method
Digital infrastructure support	*DIS*	Respondents' satisfaction with digital infrastructures such as the campus network and the library
Household digital resource supply	*HRS*	The degree of support provided by family digital devices and resources (such as software, databases, online courses) for study/work
Curriculum adaptability	*CA*	The performance of institution-offered digital literacy courses in terms of structural rationality and goal clarity
Household digital support attitude	*HAS*	The family's attitude towards supporting the improvement of digital literacy
Self-growth drive	*SGD*	The willingness to actively learn digital skills for self-growth and career development
Interest drive	*ID*	The degree of interest in exploring digital tools, platforms, or information technology
Independent practice drive	*IPD*	The behavioral tendency to actively try new digital tools even without external requirements

Calibration. Calibration is a prerequisite step for fsQCA analysis, designed to determine the degree to which each case belongs to a particular set (Wagemann et al., 2016). In this study, direct calibration is employed, using the 10th percentile, median, and 90th percentile as anchor points for each causal condition to enhance robustness. Descriptive statistics and calibration anchors for the causal conditions are presented in Table 2.

Table 2 Calibrations and descriptive statistics.

Variables	Fuzzy-set calibration			Description of sampling				
	Fully in	Crossover	Fully out	Mean	SD	Minimum	Median	Maximum
Digital infrastructure support (DIS)	5	5	3	4.325	0.819	1	5	5
Household digital resource supply (*HRS*)	5	4	3	3.98	1	1	4	5
Curriculum adaptability (*CA*)	5	4	3	4.066	0.932	1	4	5
Household digital support attitude (*HAS*)	5	4	3	4.28	0.836	1	4	5
Self-growth drive (*SGD*)	5	5	3	4.439	0.723	2	5	5
Interest drive (*ID*)	5	4	3	4.336	0.772	1	5	5
Independent practice drive (*IPD*)	5	4	3	4.161	0.86	1	5	5

Results

Necessity analysis. This study employed two necessity analysis methods, fsQCA and NCA, to achieve methodological complementarity. fsQCA identifies necessary conditions by calculating the consistency and coverage of causal conditions relative to the outcome. It emphasizes the qualitative dimension of defining which factors constitute necessary conditions for the outcome. NCA further builds on this by clarifying from a quantitative perspective how specific levels of a factor become necessary for the corresponding outcome. It focuses on measuring the extent to which causal conditions constrain students' digital literacy and determines the minimum threshold required to achieve a given level of competence.

Applying fsQCA, each causal condition was tested for necessity with respect to both high and non-high digital literacy. As shown in Fig. 2, no condition reached the conventional 0.90 threshold for necessity consistency (Ragin, 2008). This indicates that among graduate students in the social sciences, no single factor independently constitutes a necessary prerequisite for digital literacy, and thus supports a configurational rather than single-cause explanatory model.

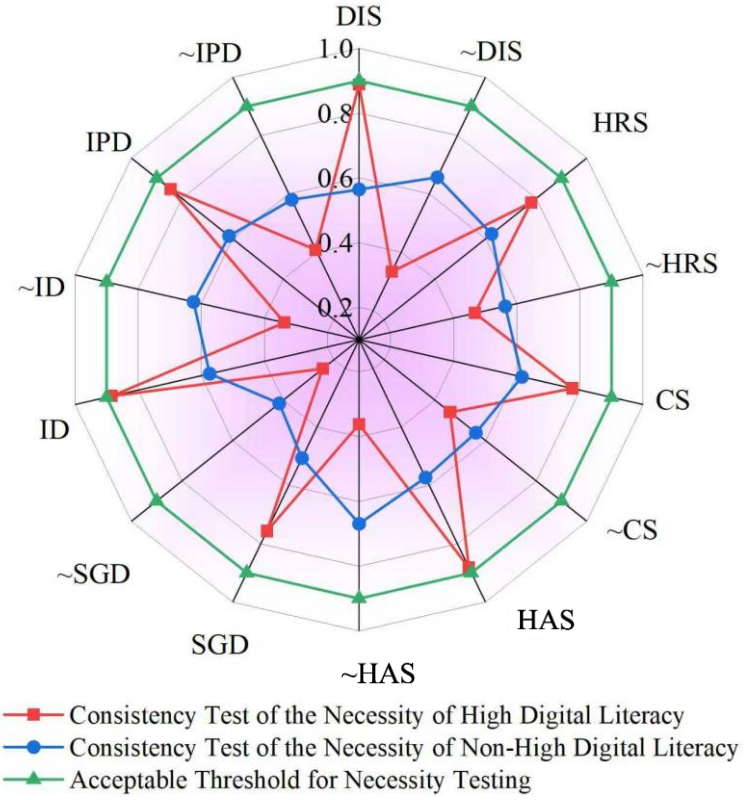


Fig. 2 Necessity test of the high digital literacy and its negation.

To further substantiate these findings, NCA was conducted to determine whether specific degrees of conditions impose structural constraints on digital literacy. NCA identifies necessary conditions by constructing scatter bottleneck plots: (1) in the XY coordinate system, a ceiling line is drawn, and the blank area above it (upper-left quadrant) indicates that when the X value is low, a high level of Y cannot be achieved

(Dul, 2016); (2) the larger the blank area, the stronger the constraining effect of that condition on digital literacy. The scatter bottleneck plot for curriculum adaptability shows a relatively small blank area in the upper-left quadrant, suggesting that curriculum adaptability exerts only a weak constraint on digital literacy. Therefore, Fig. 3 presents only the scatter bottleneck plots of the remaining six causal conditions. As shown in Fig. 3, the scatter plots of household digital support attitude (*HAS*) and interest drive (*ID*) display relatively large upper-left blank areas, preliminarily indicating that these causal conditions may be necessary for digital literacy. However, it is necessary to further examine the effect size indicators of each causal condition to confirm whether their necessity holds statistical significance.

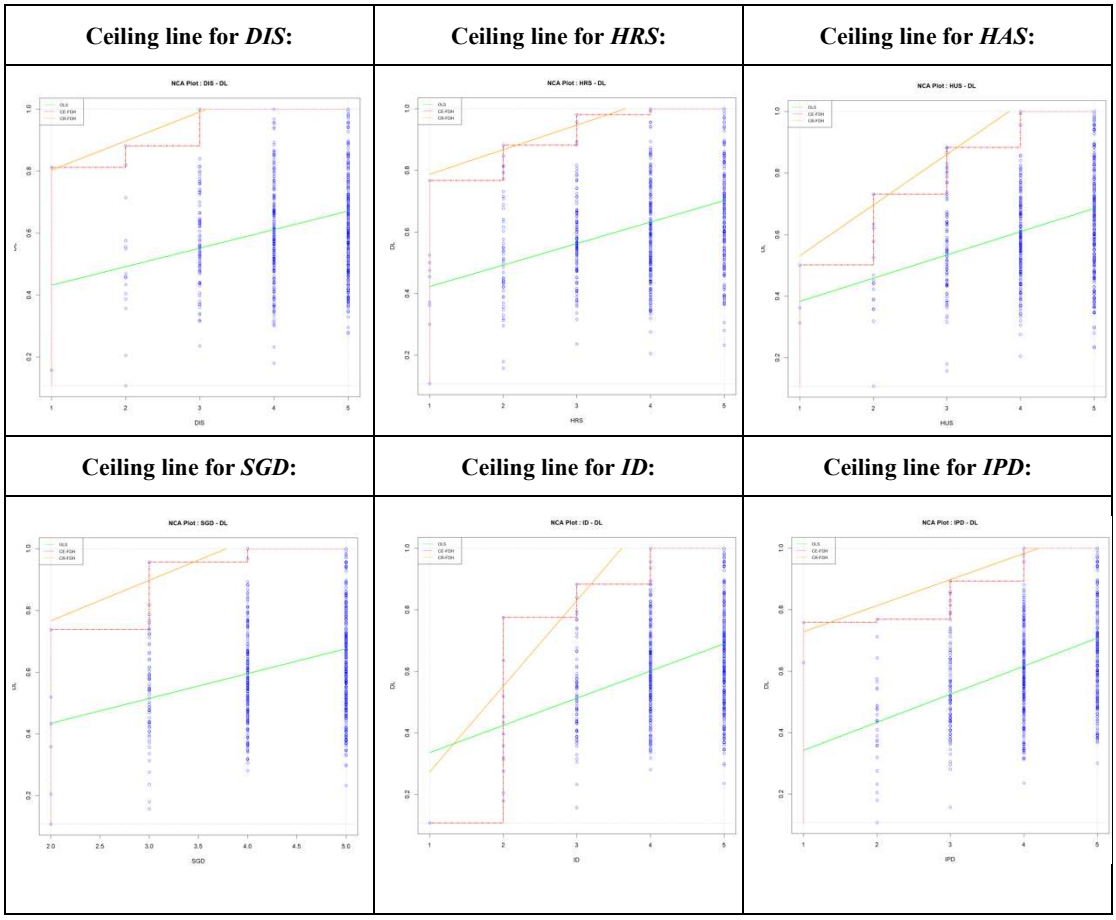


Fig. 3 Scatterplot and bottleneck analysis with ceiling lines of six causal conditions.

Based on the aforementioned intuitive bottleneck plots, NCA further verifies the constraining effect of necessary conditions in Fig. 3 by measuring the effect size (degree). The classification standards for effect size are as follows: $0 \leq d < 0.1$ indicates a "small effect," $0.1 \leq d < 0.3$ a "medium effect," $0.3 \leq d < 0.5$ a "large effect," and $d \geq 0.5$ an "extremely strong effect" (Dul, 2016). For discrete and continuous variables, effect sizes are calculated using two distinct methods: Ceiling Envelopment (CE) and Ceiling Regression (CR), respectively. Since CE is more suitable for discrete variables, the scale data in this study were analyzed using the CE method. Within the NCA

framework, a condition is recognized as necessary if it meets three criteria: theoretical justification, an effect size d greater than 0.1, and a p-value less than 0.05 (Dul et al., 2020).

Overall, most causal conditions do not constitute statistically significant necessary conditions for digital literacy. Self-growth drive (d=0.114) falls within the medium-effect range but does not pass the significance test. By contrast, interest drive (d=0.346, $p<0.05$) and household digital support attitude (d=0.248, $p<0.05$) meet the effect-size threshold and pass the NCA significance test (Fig. 4), and are therefore identified as statistically significant necessary but not sufficient conditions for achieving high digital literacy among graduate students in the social sciences.

Table 3 Analysis results of necessary conditions for the NCA method.

Variables	Method	Accuracy	Ceiling zone	Scope	Effect size	*p* value
DIS	CE	100%	0.307	3.568	0.086	0.507
	CR	99.7%	0.205	3.568	0.057	0.347
HRS	CE	100.0%	0.371	3.568	0.094	0.004
	CR	99.5%	0.283	3.568	0.079	0.001
CA	CE	100.0%	0.355	3.568	0.099	0.04
	CR	99.4%	0.269	3.568	0.075	0.004
HAS	CE	100.0%	0.885	3.568	0.248	0.001
	CR	99.4%	0.666	3.568	0.187	0.001
SGD	CE	100.0%	0.305	2.676	0.114	0.086
	CR	99.8%	0.207	2.676	0.077	0.009
ID	CE	100.0%	1.234	3.568	0.346	0.001
	CR	99.4%	0.947	3.568	0.265	0.001
IPD	CE	100.0%	0.579	3.568	0.092	0.023
	CR	99.7%	0.436	3.568	0.122	0.003

Note: permutation test in NCA analysis (resampling = 10,000). *, **, *** indicate $p < 0.1$, 0.05, 0.01, respectively.

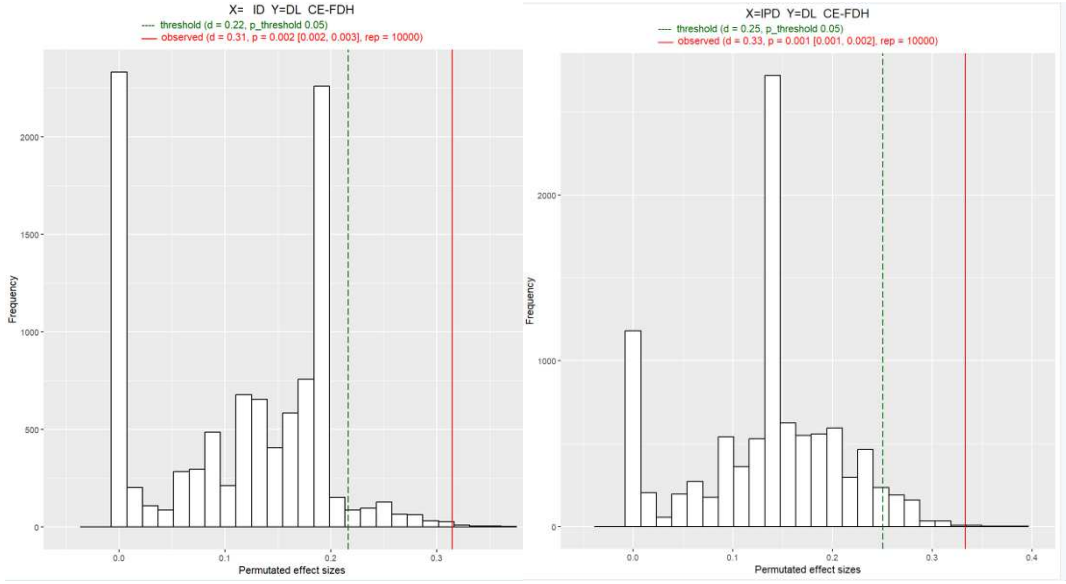


Fig. 4 Significance test of necessary conditions.

It should be noted that under the NCA framework, "necessary conditions" here refer to "necessary but not sufficient conditions," meaning that the absence of the condition will lead to the absence of the outcome (no X, no Y). This differs from QCA, where "necessary and sufficient conditions" imply that a sufficient combination of conditions leads to the outcome (X leads to Y) (Dul et al., 2020). Although interest drive and household digital support attitude were identified as necessary conditions in NCA, they may still form synergistic effects with other conditions in QCA configuration analysis, thereby reinforcing the complex mechanism that "necessary conditions can combine with sufficient conditions."

Configurational analysis of high digital literacy. Drawing on prior research (Du & Kim, 2021), the raw consistency threshold was set at 0.8, the PRI consistency threshold at 0.8, and the case frequency threshold at 2, in accordance with the distribution of the truth table and case counts. By comparing intermediate and parsimonious solutions, the analysis identified core and peripheral conditions. The fsQCA results are presented in Table 4. Among them, S1a and S1b share the same core conditions and thus form a second-order equivalent configuration. Similarly, S2a and S2b also form a second-order equivalent configuration. The overall solution consistency is 0.755, indicating that 75.5% of graduate students in the social sciences, in cases consistent with these five configurational pathways, indeed demonstrated high digital literacy.

At the same time, as shown in Table 4, all configurations have a consistency value exceeding the acceptable threshold of 0.7, confirming the validity of the configurational analysis results. Based on the commonalities of the core conditions across the five pathways, and considering the mechanism of digital literacy formation in the context

of social science graduate education, the five configurational pathways were further grouped into three broader configurational patterns.

Table 4 High digital literacy configuration.

Causal conditions	Solutions for high digital literacy				
	S1a	S1b	S2a	S2b	S3
DIS	⊗	⊗	⊗	⊗	⊗
HRS	⊗	●	⊗	⊗	
CA	●	●	⊗	●	
HAS		⊗	⊗	●	●
SGD	●	⊗	●	⊗	●
ID	●	●	⊗	⊗	●
IPD		●	●	●	●
Subset Consistency	0.711	0.832	0.766	0.825	0.752
Raw Coverage	0.298	0.150	0.199	0.164	0.652
Unique Coverage	0.015	0.008	0.020	0.008	0.022
Overall Solution Consistency			0.755		
Overall Solution Coverage			0.713		

Note: ●=core condition present, ⊗=core condition absent, ●=peripheral condition present, ⊗=peripheral condition absent; blank = condition level does not affect configuration outcome.

(1) Interest–curriculum synergy path (S1a–S1b). This mode comprises configurations S1a and S1b, both of which share two core conditions: high curriculum adaptability and high interest drive. It captures a pathway through which students improve their digital literacy through the synergy between strong intrinsic interest and well-matched curricular design, even when digital infrastructure and family support are relatively weak. This mode is therefore labeled the interest–curriculum synergy path.

Configuration S1a indicates that high digital literacy is produced by the joint presence of high curriculum adaptability and high interest drive as core conditions. Its peripheral conditions include the absence of high digital infrastructure support, the absence of high household digital resource supply, and high self-growth drive. This pathway has a consistency of 0.711 and a raw coverage of 0.298. This configuration suggests that when course design is closely aligned with learners' interests and disciplinary needs, interest can be translated into sustained learning engagement and practical skill development. In this sense, the synergy between curriculum and interest, rather than hardware investment alone, becomes the main driver of digital literacy improvement. This pathway is particularly likely among students from less advantaged backgrounds whose institutional and household digital resources are limited, but who nevertheless achieve substantial gains through a strong match between interest and

curricular support.

Configuration S1b also identifies high curriculum adaptability and high interest drive as the core conditions for high digital literacy. However, its peripheral conditions shift to the absence of high digital infrastructure support, high household digital resource supply, the absence of high household digital support attitude, and the absence of high self-growth drive. This pathway has a consistency of 0.832 and a raw coverage of 0.150. The configuration shows that the joint effect of interest and curriculum can still generate high digital literacy even when family attitudes are not especially supportive and institutional infrastructure remains limited. In this pathway, household resources and students' own learning efforts appear to function as compensatory supports that reinforce the core interest–curriculum synergy.

Comparing S1a and S1b, both configurations share the same dual core conditions, but differ in the way peripheral conditions compensate for environmental deficiencies. The defining feature of this pathway is that strong alignment between curriculum design and learner interest provides the central mechanism through which high digital literacy is achieved.

(2) Independent-practice-dominant path (S2a–S2b). This mode comprises configurations S2a and S2b. Its core conditions center on the absence of high interest drive and the presence of high self-growth drive. It reflects a pathway in which autonomous practice offsets both motivational and environmental deficiencies. This mode is therefore labeled the independent-practice-dominant path.

In configuration S2a, the core conditions for high digital literacy are the absence of high interest drive and high self-growth drive. Its peripheral conditions include high digital infrastructure support, the absence of high household digital resource supply, the absence of high curriculum adaptability, and the absence of high household digital support attitude. This pathway has a consistency of 0.766 and a raw coverage of 0.199. The configuration suggests that when learners possess strong self-directed practice and a clear orientation toward self-development, they can overcome weak interest and limited environmental support. In this pathway, autonomous engagement with digital tools becomes the central mechanism through which digital literacy is improved.

In configuration S2b, the core conditions remain high self-growth drive and the absence of high interest drive, while the peripheral conditions shift to high household digital resource supply, high household digital support attitude, high interest drive, the absence of high digital infrastructure support, and the absence of high independent practice drive. This pathway has a consistency of 0.825 and a raw coverage of 0.164. It shows that high digital literacy can still emerge when learners actively create their own opportunities for practice and skill development, even without strong institutional infrastructure. Here again, the key mechanism lies in the capacity for self-initiated

learning and practice, which compensates for weaknesses in other internal or environmental conditions

Taken together, S2a and S2b indicate that the defining feature of this pathway is the dominant role of autonomous practice and self-development. Under this pattern, insufficient interest, limited curricular support, or weak environmental conditions do not necessarily prevent students from attaining high digital literacy.

(3) Self-growth–practice synergy path (S3). This mode corresponds to configuration S3, whose core conditions are high self-growth drive and high independent practice drive. Its peripheral conditions include the absence of high digital infrastructure support, high household digital support attitude, and high interest drive. It captures a process through which students achieve breakthroughs in digital literacy under constrained environmental conditions by combining strong self-development goals with sustained practice. This mode is therefore labeled the self-growth–practice synergy path.

This configuration suggests that when institutional digital infrastructure is relatively limited, self-growth drive activates an endogenous motivation to pursue skill development, while independent practice translates that motivation into concrete capability gains. In this pathway, environmental deficiencies are not simply obstacles; rather, they become conditions that prompt students to seek alternative learning strategies and practice opportunities. The core mechanism of this pathway thus lies in the synergy between self-growth drive and active practice, through which students convert limited external support into a catalyst for digital literacy development.

The three differentiated pathways reveal the asymmetric mechanisms of environmental deficiency–individual compensation and environmental advantage–individual response, thereby supporting the applicability of PEF theory to the cultivation of digital literacy (Schmitt et al., 2017). A further comparison of these pathways shows that self-growth drive appears across four high-digital-literacy configurations as either a core or peripheral condition, while the main differences lie in how specific constraints are overcome. The interest–curriculum synergy path highlights the role of intrinsic interest and curricular fit in compensating for resource constraints. The independent-practice-dominant path shows how autonomous practice can substitute for weak interest or environmental support. The self-growth–practice synergy path underscores the role of practice in overcoming deficiencies in digital infrastructure. These findings suggest that, alongside improvements in infrastructure and curriculum systems, greater attention should be paid to activating students' intrinsic learning motivation and building coordinated support networks across the family, institution, and individual levels, especially by creating more opportunities for practice and development for students with limited resource endowments.

Non-high digital literacy configuration. To examine causal asymmetry, configurations leading to non-high digital literacy were analyzed, and four solutions were identified. NS1 shows that when household digital resource supply and curriculum adaptability as core conditions are lacking, and digital infrastructure support, self-growth drive, interest drive, and independent practice drive only exist as peripheral conditions, students' digital literacy remains low. NS2 shows that when household digital resource supply as a core condition are absent, even with digital infrastructure support, curriculum adaptability, self-growth drive, interest drive, and independent practice drive as peripheral conditions, students do not achieve high literacy. NS3 shows that if independent practice drive as a core condition is absent, then even with digital infrastructure support, household digital resource supply, curriculum adaptability, self-growth drive, and interest drive as peripheral conditions, students still fail to achieve high literacy. NS4 shows that when curriculum adaptability as a core condition is lacking, even the presence of other peripheral conditions cannot ensure high literacy.

Thus, low independent practice drive ($IPD < 0.5$) and low curriculum adaptability ($CA < 0.5$) are key constraints. For instance, some students experience a "double deficiency" of weak household support ($HAS < 0.3$) and poor digital infrastructure support ($DIS < 0.4$), leading to long-term stagnation in digital literacy. This reveals the asymmetry with high-literacy paths: environmental deficiencies can be compensated, but dual deficiencies in practice willingness and curriculum quality are particularly destructive and must be prioritized for intervention.

Robustness tests. To assess the robustness of the configurational results, this study re-estimated the fsQCA solutions by adjusting the analytical thresholds. Specifically, the consistency threshold was raised from 0.80 to 0.85, while the PRI consistency threshold and case frequency threshold were retained for comparison. The results show that the overall configuration patterns remained substantively consistent with the main findings, with no notable changes in the core conditions or the broader pathway structure. This indicates that the configurational results are robust.

Discussion

This study speaks to the ongoing debate over whether graduate students' digital literacy is driven mainly by hardware provision or by the interplay among technological resources, the broader learning environment, and learner motivation. Drawing on Person–Environment Fit theory and a sequential mixed-methods design, the findings show that high digital literacy does not arise from the linear accumulation of resources alone, but from the alignment of environmental support with individual motivation.

The three configurational paths identified here are best understood in the context of social science graduate education. Unlike STEM (Science, Technology, Engineering, and Mathematics) disciplines, which often depend on highly specialized laboratory hardware and standardized software systems, graduate education in the social sciences typically places less emphasis on advanced technical equipment and more on access to information, analytical interpretation, communication, and context-sensitive problem solving. In this context, digital literacy is not limited to technical proficiency; it also involves the ability to retrieve, evaluate, integrate, and communicate information effectively across diverse academic and practical settings.

In social science graduate education, the interplay between hard and soft environments appears to depend less on resource intensity than on functional fit. The findings suggest that while hardware (*DIS*) provides the basic conditions for connectivity and access, soft elements—such as curriculum adaptability and supportive learning environments—play a more prominent role in moving students from basic operation to higher-order inquiry, analysis, and problem solving. This helps explain why the absence of high-end hardware does not necessarily preclude high digital literacy when strong individual agency (*SGD* or *IPD*) is present. This disciplinary context also helps explain the compensatory mechanisms observed in our results: for social science graduate students, the digital environment functions less as a purely technical laboratory than as an enabling infrastructure for knowledge work, academic communication, and socio-technical interaction.

Theoretical implications. First, this study extends person–environment fit (PEF) theory by showing that fit in digital literacy development is not a singular match between one personal trait and one environmental condition, but a multidimensional and configurational alignment among environmental hard conditions, environmental soft conditions, and individual intrinsic motivation. Prior PEF research has consistently shown that fit is associated with more favorable attitudes, performance, and persistence outcomes (Kristof-Brown et al., 2005), and educational technology research has further suggested that perceived fit and learning support shape students' sustained engagement with digital learning tools (Ifinedo, 2018). Building on this line of work, our findings suggest that digital literacy should be understood as an emergent outcome of multiple forms of fit rather than as the direct product of any single factor. In this sense, the study moves PEF theory from a relatively linear fit–outcome logic toward a more dynamic view in which environmental deficiencies may be compensated for by learner motivation, and different combinations of fit may still lead to the same high-level outcome.

Second, this study contributes to the digital literacy literature by challenging interpretations that either reduce digital literacy to the possession of technical resources

or simplify its cultivation into a binary opposition between "hardware priority" and "software-hardware synergy" (Falch, 2022; Li et al., 2021). Existing scholarship has long argued that digital literacy is multidimensional rather than purely technical (Ng, 2012; Eshet, 2012). At the same time, recent reviews of educational digital transformation have shown that digital outcomes depend not only on infrastructure, but also on broader forms of digital capacity, organizational support, and pedagogical arrangements (Timotheou et al., 2023). Our findings refine this literature in two ways. On the one hand, they show that digital literacy among graduate students in the social sciences is shaped not simply by access to devices or platforms, but by how technological resources are aligned with curriculum adaptability, family support, and learner motivation. On the other hand, they suggest that higher-order domains such as digital application, creative problem-solving, and practice-oriented engagement are especially salient in this context. Theoretically, this shifts the focus of digital literacy research from resource possession to socio-technical alignment.

Third, this study advances the theorization of digital literacy development by adopting a neo-configurational perspective. Configurational research argues that causal complexity is characterized by conjunctural causation, equifinality, and causal asymmetry, and therefore cannot be adequately captured through net-effect logic alone (Fiss, 2011; Misangyi et al., 2017). By combining NCA and fsQCA, this study shows that the mechanisms leading to high digital literacy are not simply the inverse of those leading to non-high digital literacy. Interest drive and household digital support attitude function as necessary but not sufficient conditions, while multiple distinct pathways can still produce the same high-level outcome. Taken together, these findings also suggest that approaches grounded primarily in linear net-effect logic may understate the causal complexity of digital literacy development (Derder et al., 2024). This finding not only supports the value of configurational reasoning in digital literacy research, but also suggests that future theory-building should move beyond asking which single factor matters most and instead examine how different conditions become effective in combination. In this respect, the study contributes to a more fine-grained understanding of digital literacy as a causally complex educational outcome.

Practical implications. Graduate students' digital literacy development depends not only on access to technological resources but also on effective institutional and policy support. It is suggested that systematic strategies be implemented to optimize digital resource allocation, enhance institutional adaptability, and strengthen individual motivation, thereby advancing both students' growth and universities' digital transformation.

Firstly, optimize resource allocation through software-hardware synergy. Institutional strategies for fostering digital literacy should move beyond hardware-

centered investment toward an integrated support ecosystem that combines infrastructure, curriculum, services, and motivational support. To address the issue of low hardware utilization, universities can establish dynamic monitoring mechanisms to track equipment use in real time, prioritizing upgrades for underperforming facilities rather than expanding coverage blindly. Resource allocation should also remain sensitive to disciplinary needs; for example, social science programs may prioritize databases and policy- or research-oriented data services over low-efficiency immersive technologies (McGann et al., 2021; Pasin & Giroux, 2011). Following the interest–curriculum synergy path identified in the configuration analysis, universities may strengthen curriculum alignment, interest-based digital learning opportunities, and targeted household support packages in resource-poor regions.

Secondly, enhance the soft environment and teaching capacity. Strengthening the soft environment is equally important. Universities can develop modular courses such as data governance case libraries, enhance faculty competence through digital literacy certification, integrate digital teaching outcomes into promotion evaluations (Jensen et al., 2025), and establish campus-level data platforms to reduce barriers in student data analysis (Basilotta et al., 2022; Pangrazio & Sefton, 2020; Zhao et al., 2021). These measures help overcome the "hardware-heavy, software-light" dilemma and address the "high device cognitive load" bottleneck, achieving more efficient resource transformation.

Thirdly, design adaptive and differentiated policy frameworks. Universities also need flexible and differentiated policy frameworks rather than one-size-fits-all interventions. Based on the fsQCA-identified multiple equivalent paths, targeted interventions can be implemented. For students on the interest–curriculum synergy path, institutions may strengthen curriculum design and interest-based project opportunities. For those on the independent-practice-dominant path, universities may expand open labs, project-based practice, and low-threshold experimentation spaces. For those on the self-growth–practice synergy path, institutions may connect self-development goals with sustained practice opportunities and mentoring support.

Fourthly, activate intrinsic motivation to promote individual empowerment. The key to individual empowerment lies in activating intrinsic motivation and translating it into practical capabilities that drive endogenous digital literacy development. Layered strategies can target different motivational systems. For students whose development relies strongly on interest activation, digital innovation competitions and open-source community activities can strengthen exploratory engagement (Detlor et al., 2022; Guillén et al., 2024). For those whose development depends more on self-growth and practice, research participation, data-based projects, and cross-disciplinary mentoring can help translate motivation into durable capability gains.

Limitations and future research. Several limitations should be taken into account in this study. First, the findings are based on cross-sectional, self-reported data, which limits causal inference and may not fully capture students' actual digital literacy. Future research could adopt longitudinal designs and incorporate more objective indicators, such as digital learning records or standardized assessments, to strengthen measurement validity. Second, the operationalization of the digital environment in this study focuses on perceived infrastructure and soft support, which may not fully reflect variation in task environments across different subfields within the social sciences. Future research could further refine the environmental construct by examining how subfield-specific task demands shape different configurational pathways. Third, although fsQCA identifies equifinal pathways to high digital literacy, it is less precise in revealing the micro-level processes through which students compensate for environmental deficiencies. Future research could combine configurational analysis with qualitative or mixed-methods approaches to explore these underlying mechanisms in greater depth.

Conclusion

This study, grounded in Person–Environment Fit theory and a sequential mixed-methods design, examined how environmental conditions and individual motivation jointly shape digital literacy among graduate students in the social sciences. The findings show that digital literacy is a multidimensional construct, with digital application and operation and digital creativity and problem-solving emerging as the most influential domains in this context. The NCA results further indicate that interest drive and household digital support attitude function as necessary but not sufficient conditions for high digital literacy, while the fsQCA results reveal three equifinal pathways through which high digital literacy can be achieved: the interest–curriculum synergy path, the independent-practice-dominant path, and the self-growth–practice path. At the same time, the analysis of non-high digital literacy suggests that low independent practice drive and low curriculum adaptability are the most critical constraints on digital literacy development. Taken together, these findings show that digital literacy does not result from the simple accumulation of technological resources, but from the configurational alignment of environmental support and individual motivation. This study therefore provides a clearer basis for understanding digital literacy development in higher education and for designing more adaptive support strategies across institutional, family, and individual levels.

Data availability

The anonymised datasets analysed in this study are available as supplementary files for editorial and peer-review purposes. The questionnaire, variable definitions, and

calibration information are provided in the manuscript and supplementary documentation. Potentially identifiable information is not shared to protect participant confidentiality.

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Appendix 1

Measurement scales for causal conditions and the outcome variable

Item No.	Item description
	Environmental hard condition
Q1	I am satisfied with my university's digital infrastructure.
Q2	My family provides the digital devices and related resources I need for study and work.
	Environmental soft condition
Q3	My university's digital literacy courses are well-designed with clear goals.
Q4	My family supports and encourages my use of digital tools.
	Individual intrinsic motivation
Q5	I seek to learn new digital skills for personal and career growth.
Q6	I enjoy exploring new digital tools and technologies.
Q7	I take initiative to learn and try new tools even without external demands.
	Digital thinking and cognition
Q8	I understand the vital role of digital technology in learning, daily life, and career development.
Q9	I prefer handling tasks digitally.
Q10	I actively monitor data trends and reflect on their meaning.
Q11	I recognize the challenges of rapid digital change and value continuous learning.
	Digital collaboration and communication
Q12	I use digital tools to visualize information and enhance communication.
Q13	I share data and references responsibly through digital platforms.
Q14	I collaborate efficiently with others using digital tools.
Q15	I often join online activities like webinars or digital projects.
	Digital application and operation
Q16	I operate digital devices proficiently for study and work.
Q17	I can install and use office, statistical, and visualization software.
Q18	I write code in Python or R.
Q19	I use Stata or SPSS for data analysis and modeling.
	Digital creativity and problem-solving

Q20	I create documents, spreadsheets, and presentations effectively.
Q21	I edit and generate new content with digital tools.
Q22	I solve technical problems during digital tool use.
Q23	I choose suitable digital solutions for study or work tasks.
	Digital ethics and security
Q24	I protect my accounts and sensitive information from breaches.
Q25	I back up important data regularly.
Q26	I act responsibly online, following digital ethics.
Q27	I respect privacy and originality, avoiding plagiarism or misuse.

Ethical approval

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments. The study was approved by the Human Research Ethics Committee of the School of Public Administration at Beihang University (Approval No. BHU-IRB-2025-087; Date: July 5, 2025).

Informed consent

Before participating in the survey, all participants were informed of the purpose of the study, the voluntary nature of participation, the confidentiality of their responses, and their right to withdraw at any time. Written informed consent was obtained from all participants before they completed the questionnaire.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Questionnaireen.docx
- Dataprocessed.xlsx
- Dataraw.xlsx
- NCAQCAanalysiscodeandresults.docx