Modeling Digital Communication and Collaboration Competence in ICT-enhanced Primary Education: A PLS-SEM Study from Vietnam

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***Abstract*—As digital technologies become increasingly integrated into primary education, understanding factors associated with students' Digital Communication and Collaboration Competence (DCCC) in Information and Communication Technologies (ICT)-enhanced learning environments has emerged as a central concern in educational research and practice. This study examines associations among Environmental Factors (EF), Internal Factors (IF), and DCCC among primary school students in Vietnam, proposing an integrated EF–IF–DCCC framework. Data were gathered from 4403 primary school students across 21 provinces using a purposive school-based sample; teacher responses (n = 918 valid responses) provided contextual interpretation and triangulation and were not included in the structural model. Partial Least Squares-Structural Equation Modeling (PLS-SEM) and multi-group analysis was used to examine structural relationships and potential group differences. The findings show that DCCC is a multidimensional construct, that EF was positively associated with both IF and DCCC, that IF was positively associated with DCCC, and that IF partially mediated the EF–DCCC relationship. Multi-group analysis revealed no significant gender differences, while significant grade-level and regional differences were observed. The results offer empirical support for an integrated framework linking EF and IF to multidimensional DCCC in Vietnamese primary education and carry practical implications for designing ICT-integrated learning environments that strengthen students' digital competence.**

***Keywords*—Digital Communication and Collaboration Competence (DCCC), Information and Communication Technologies (ICT)-enhanced learning, primary education, environmental and internal factors, Partial Least Squares-Structural Equation Modeling (PLS-SEM)**

I. Introduction

The rapid expansion of digital technologies has fundamentally transformed how individuals communicate, collaborate, and learn. As digital tools become increasingly integrated into educational systems, the development of students' digital competence has emerged as a central priority in both educational policy and research. International frameworks consistently emphasize communication and collaboration as core components of digital competence. For instance, the European Digital Competence Framework (DigComp) positions communication and collaboration as a key domain covering interaction, information sharing, collaborative practices, and digital identity management [1]. Similarly, UNESCO's Digital Literacy Global Framework highlights communication, collaboration, and responsible participation in digital environments as essential competencies for learners in the twenty-first century [2].

In many education systems, including Vietnam, digital competence has become a strategic priority in educational reform, with growing efforts to integrate Information and Communication Technologies (ICT) into teaching and learning practices. The Vietnamese Ministry of Education and Training has introduced a national Digital Competence Framework for learners, in which digital communication and collaboration are identified as one of the six core competencies to be developed throughout schooling [3]. This reflects a growing recognition that students must be able to effectively communicate and collaborate in digitally mediated environments.

From a theoretical perspective, the development of digital competence can be understood as the result of interactions between individual characteristics and environmental conditions. Ecological frameworks of human development propose that learning outcomes arise through the dynamic interplay between individuals and their surrounding contexts [4]. In parallel, self-regulated learning theory underscores the role of internal factors—such as motivation, attitudes, and self-efficacy—in shaping students' engagement with learning tasks [5]. Empirical studies have shown that both contextual conditions—such as access to digital technologies, family support, and teachers' digital competence—and internal factors are associated with students' digital learning experiences and skill development [6, 7].

Digital competence and technology-enhanced learning in school contexts have attracted substantial research attention. Studies have documented the role of educational environments, access to technology, and instructional practices in shaping students' digital skills [8, 9]. Other research has emphasized the role of family environments in shaping students' confidence in using digital technologies [10, 11], as well as the potential of digital tools to support collaborative learning and communication skills [12, 13].

Despite this growing body of research, several important gaps remain. First, existing studies have predominantly focused on secondary or higher education contexts, with comparatively limited attention given to primary school students. However, early engagement with digital technologies may play a critical role in shaping students' later digital competence [14, 15]. Second, prior research often examines determinants of digital competence in isolation, with some studies focusing on technological infrastructure and others on psychological variables such as attitudes or

motivation. Empirical models that integrate both environmental and internal factors remain relatively limited. Third, many studies rely on data from a single stakeholder group, such as students or teachers, which may constrain a comprehensive understanding of digital competence development.

Addressing these gaps is important for advancing both theory and practice. A more integrated understanding of how environmental and internal factors are associated with digital communication and collaboration competence can provide a stronger basis for designing effective ICT-enhanced learning environments, particularly in early education contexts. In addition, incorporating perspectives from multiple stakeholders may provide a fuller picture of the factors and processes through which students' digital competence develops.

Therefore, this study aims to examine the relationships among Environmental Factors (EF), Internal Factors (IF), and Digital Communication and Collaboration Competence (DCCC) among primary school students in Vietnam. The proposed EF–IF–DCCC model is grounded in ecological and self-regulated learning perspectives [4, 5]. EF refer to contextual conditions supporting digital learning, including technological infrastructure, family support, and teachers' digital competence. IF represent students' attitudes toward technology, learning experiences, and confidence in using digital tools, while DCCC is conceptualized as the outcome emerging from the interaction between these factors.

This study uses survey data collected from 4403 primary school students across 21 provinces in Vietnam, complemented by responses from 918 teachers to support data triangulation. Partial Least Squares-Structural Equation Modeling (PLS-SEM) is employed to analyze the relationships among the proposed variables.

This study makes three main contributions. First, it provides large-scale empirical evidence on digital competence development among primary school students, a population that remains underexplored in existing research. Second, it proposes and validates an integrated structural model—the EF–IF–DCCC model—that examines how environmental and internal factors are associated with students' digital communication and collaboration competence. Third, it provides evidence that internal factors partially mediate the relationship between environmental factors and DCCC, suggesting that the association between learning environments and digital competence may operate partly through students' engagement, confidence, and attitudes toward digital technologies.

Based on these considerations, the study addresses the following research questions:

(1) What are the associations among Environmental Factors (EF), Internal Factors (IF), and Digital Communication and Collaboration Competence (DCCC) among primary school students in Vietnam?
(2) Do the structural relationships in the EF–IF–DCCC model vary according to student gender, grade level, and geographic region?

II. Literature Review

A. Digital Communication and Collaboration Competence

Digital Communication and Collaboration Competence (DCCC) has emerged as a widely recognized component of digital competence in contemporary education systems. International frameworks such as the European Digital Competence Framework conceptualize digital competence as a multidimensional construct that encompasses the knowledge, skills, and attitudes needed for meaningful participation in digital environments [1]. Within this framework, communication and collaboration allow learners to engage, exchange information, and contribute responsibly within digital communities. Recent reviews similarly identify communication and collaboration as core dimensions of digital literacy and digital competence [16].

In line with these perspectives, DCCC is conceptualized in this study as a second-order construct comprising six dimensions: Interacting through Digital Technologies (INT), Sharing Information and Content through Digital Technologies (SHR), Engaging and Contributing as a Digital Citizen through Digital Technologies (ENG), Collaborating through Digital Technologies (COL), Netiquette (NET), and Managing Digital Presence and Identity (MDI). These dimensions reflect both technological and socio-ethical aspects of participation in digital environments and are consistent with recent measurement approaches in digital competence research [17].

The growing integration of digital technologies into education has created new opportunities for collaborative learning and social interaction. Online environments enable students to exchange ideas, take part in shared activities, and build knowledge collectively [13, 18]. Technology-supported learning activities have also been shown to strengthen communication and information-sharing skills [19]. At the primary school level, early experiences with digital communication may strengthen teamwork, participation, and engagement within technology-enhanced learning environments [20]. These findings highlight the importance of examining how DCCC develops in early educational contexts.

Furthermore, recent empirical evidence suggests that technology-supported collaborative environments, particularly cloud-based tools, can enhance students' communication, teamwork, and engagement through features such as real-time interaction, shared workspaces, and continuous feedback [21].

Understanding the development of DCCC therefore requires examining both the contextual conditions that shape students' access to and experience with digital technologies and the internal characteristics that students themselves bring to these interactions. Environmental factors such as technological infrastructure, teacher competence, and family support establish the setting within which students develop digital skills, while internal factors such as self-efficacy, motivation, and attitudes reflect the individual resources students bring to digital learning tasks. These two categories of factors, and the relationships through which they are associated, form the conceptual basis of the research model examined in this study.

B. Internal and Environmental Influences on DCCC

The development of digital competence can be understood in terms of interactions between individual characteristics and environmental conditions. Ecological and sociocultural

perspectives hold that learning outcomes are associated with such interactions [4, 22]. Drawing on these frameworks, this study approaches DCCC as a developmental competence associated with both the contextual conditions students encounter and the internal dispositions they bring to digital learning environments.

Internal Factors (IF) refer to students' attitudes and dispositions toward digital technologies. Students who exhibit higher levels of confidence and motivation are more likely to actively engage in digital communication and collaborative learning activities, as these internal factors are central to shaping engagement and learning outcomes in technology-mediated environments [11, 23].

Environmental Factors (EF), in contrast, represent the technological and social contexts in which learning occurs. Family and school environments offer access to digital resources and opportunities to develop digital skills [6, 7]. Family–school interactions and communication have also been recognized as key factors in supporting the development of students' digital skills [14, 24]. School contexts are especially significant, as teachers' digital competence and the integration of digital tools into classroom practices can generate opportunities for collaborative learning and foster the development of communication and collaboration skills [9, 25].

Taken together, these perspectives suggest that DCCC is shaped by the interaction between environmental conditions and students' internal learning processes. However, the relationships among these factors require further empirical investigation.

C. Research Gaps

Despite this body of evidence on digital competence, several notable gaps persist. First, empirical evidence on DCCC in primary education contexts is limited compared to secondary and higher education [15, 26]. Primary school years represent a formative period in which foundational dispositions toward digital engagement are established, yet this context remains underrepresented in the empirical literature, particularly in developing-country settings.

Second, prior research has tended to examine environmental and internal factors in isolation rather than as complementary influences. Studies have focused either on technological infrastructure and school or family context, or on students' internal dispositions such as attitudes and self-efficacy—without modeling how these two factor types are jointly associated with digital competence. The present study addresses this by integrating both within the EF–IF–DCCC structural model.

Third, DCCC as a specific and multidimensional component of digital competence has received limited empirical attention in primary school contexts. Existing work has tended to apply broad digital competence frameworks rather than validated, construct-specific models of communication and collaboration competence [27, 28]. The present study addresses this gap by conceptualizing DCCC as a second-order construct comprising six dimensions and testing its structural associations with EF and IF.

Taken together, these gaps indicate the need for research that integrates environmental and internal factors within a structural model, operationalizes DCCC as a multidimensional construct, and applies this framework in primary education contexts in developing countries. The present study responds to all three through the EF–IF–DCCC model, drawing on data from 4,403 students across 21 provinces in Vietnam.

III. Conceptual Framework and Research Hypotheses

To address the identified gaps, this study adopts a conceptual framework grounded in the Person–Environment Interaction perspective, which posits that learning outcomes are associated with the interplay between individual characteristics and environmental conditions [4, 5]. This perspective was selected because it explicitly integrates both contextual and individual-level influences within a single analytical lens, aligning directly with the study's focus on Environmental Factors (EF) and Internal Factors (IF) as complementary predictors of DCCC. Unlike perspectives that address contextual conditions or individual dispositions in isolation, the Person–Environment Interaction framework provides a theoretically coherent basis for examining how EF and IF are jointly associated with students' digital communication and collaboration competence.

Within this framework, Environmental Factors (EF), including technological infrastructure, family support, and teachers' digital competence, represent contextual conditions surrounding students' digital learning opportunities. These factors are expected to be associated with Internal Factors (IF), such as students' attitudes, motivation, and confidence in using digital technologies.

Internal factors are expected to directly influence students' ability to communicate and collaborate in digital environments. Students with higher levels of confidence and engagement are more likely to actively participate in digital communication and collaborative learning activities. In this sense, IF may mediate the relationship between environmental conditions and DCCC.

In addition, background characteristics such as gender, grade level, and area of residence may influence students' opportunities to develop digital competence. These variables are therefore included to examine potential group differences.

Based on this framework, the following hypotheses are proposed:

H1: Environmental factors positively influence internal factors.

H2: Environmental factors positively influence digital communication and collaboration competence.

H3: Internal factors positively influence digital communication and collaboration competence.

H4: Environmental factors indirectly influence DCCC through internal factors.

H5a–c: The structural relationships among EF, IF, and DCCC differ according to gender (H5a), grade level (H5b), and area of residence (H5c).

To test these hypotheses, this study employs Partial Least Squares-Structural Equation Modeling (PLS-SEM), which enables the simultaneous estimation of measurement and structural models and supports multigroup comparisons [29, 30]. The conceptual research model illustrating these hypothesized relationships is presented in Fig. 1.

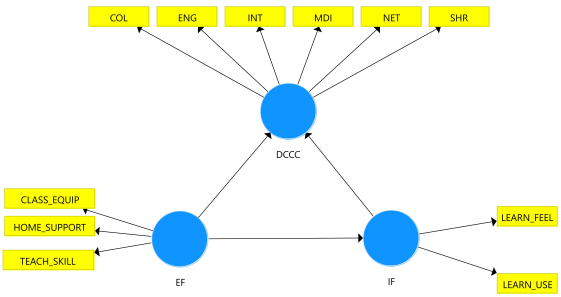


Fig. 1. Conceptual research model of the EF–IF–DCCC relationships.

IV. Materials and Methods

A. Research Design

This study adopted a quantitative research design to examine factors influencing primary school students' Digital Communication and Collaboration Competence (DCCC). Data were gathered through a structured survey administered in both online and paper-based formats across multiple provinces in Vietnam. Two complementary data sources were used: a structured student survey, which served as the primary empirical basis for testing the proposed structural model, and a separate teacher survey, which provided descriptive, practitioner-level information used to contextualize and corroborate the interpretation of the student-based findings.

To test the proposed conceptual model, Partial Least Squares-Structural Equation Modeling (PLS-SEM) was employed. This method is well-established in educational research for analyzing complex relationships among latent variables and hierarchical constructs [29, 30]. PLS-SEM supports the joint estimation of measurement and structural models and accommodates survey data that may deviate from normality assumptions. The structural model was estimated using the student dataset only. The student questionnaire captured first-person experiential reports of the constructs in the proposed model (e.g., students' own experience of family support, classroom infrastructure, and learning-related attitudes), whereas the teacher questionnaire asked teachers to rate, in general terms, how strongly they believed such factors influence students' competence—an evaluative judgment rather than a first-person measure of the same constructs. Because these two forms of data reflect different measurement logics, combining them within a single structural model would risk conflating distinct constructs under shared variable labels; the teacher data were therefore examined descriptively, as a complementary source of contextual corroboration, rather than incorporated into the structural estimation. In addition, Multi-Group Analysis (MGA) was applied to assess potential differences in DCCC across gender, grade level, and area of residence.

B. Participants

Participants were primary school students from multiple regions of Vietnam. A total of 5294 students completed the survey. After data screening and removal of incomplete responses, 4403 valid questionnaires were retained for analysis. The sample included students from 21 provinces and municipalities representing the northern, central, and southern regions of the country. Schools were recruited through a purposive, school-based sampling strategy designed to capture contextual diversity rather than statistical representativeness; selection deliberately spanned metropolitan urban districts, provincial urban areas, rural areas, and remote areas across these provinces.

Regarding grade level, 28.9% of participants were in Grade 3, 37.9% in Grade 4, and 33.2% in Grade 5. The gender distribution was relatively balanced, with 47.7% male and 52.3% female students. In terms of residential context, 22.4% lived in centrally governed cities, 30.9% in provincial urban areas, 30.1% in rural areas, and 16.6% in remote or mountainous regions. Because schools were selected purposively rather than through probability-based sampling, the resulting sample constitutes a large-scale purposive school-based sample rather than a nationally representative one, and the findings should accordingly be interpreted within this sampling context rather than generalized to the broader national population.

In addition, 996 primary school teachers from the same participating schools as the student respondents participated in the survey, of whom 918 responses were valid. Teachers had an average age of approximately 40 years and an average teaching experience of about 15 years. Teacher responses were used to triangulate and support the interpretation of the student survey results but were not included directly in the structural equation model.

C. Instruments and Variables

The survey instruments were developed based on the national digital competence framework for learners and aligned with international digital literacy frameworks [1–3]. Both instruments were constructed specifically for this study rather than adopted from an existing published scale: items were written in Vietnamese and framed as scenarios reflecting situations familiar to Vietnamese primary school students and teachers. The student and teacher questionnaires were organized around the same six competence dimensions named in the national framework, which also provided the structural basis for aligning the instruments with the international frameworks cited alongside it. Two questionnaires were designed: one for students and one for teachers.

The student questionnaire consisted of 30 items. Eleven items captured background characteristics and contextual variables, while 19 items assessed digital communication and collaboration competence. The competence construct encompassed six dimensions: Interacting through Digital Technologies (INT), Sharing Information and Content through Digital Technologies (SHR), Engaging and Contributing as a Digital Citizen through Digital Technologies (ENG), Collaborating through Digital Technologies (COL), Netiquette (NET), and Managing Digital Presence and Identity (MDI). Items were formulated as brief scenarios drawn from contexts familiar to primary school students and scored on a four-level scale from 0 to 3. For example, one item assessing collaboration described a situation in which group members could not meet in person to complete a shared task, with response options ranging from not knowing which tool to use to combining a document-editing platform for joint writing with a messaging application for discussion; another item assessing netiquette presented a scenario in which a classmate sent a message

teasing another student online, with options ranging from joining in the teasing to sending the affected classmate a supportive message and asking the other student to stop.

The teacher questionnaire included 18 items corresponding to the same six competence dimensions. Teachers evaluated students' competence using a four-level scale and assessed the influence of environmental conditions on students' digital learning using a five-point Likert scale ranging from 0 (no influence) to 4 (very strong influence).

The research model included three groups of variables. Background variables included grade level, gender, and area of residence. Environmental Factors (EF) comprised family support (HOME_SUPPORT), classroom technological infrastructure (CLASS_EQUIP), and teachers' digital competence (TEACH_SKILL). Internal Factors (IF) encompassed students' feelings when learning with digital technologies (LEARN_FEEL) and their frequency of technology use for learning activities (LEARN_USE). The dependent variable was DCCC, operationalized as a reflective higher-order construct encompassing the six competence dimensions. For instance, CLASS_EQUIP was measured by asking students how often technological equipment such as computers, projectors, or smart boards was available and used in their classroom, while LEARN_FEEL was measured by asking students how they felt when studying with digital devices, with response options ranging from finding it difficult or being afraid of making mistakes to feeling confident enough to help classmates.

During preliminary analysis, the variable HOME_DEVICE was removed because all students reported having access to a digital device at home, yielding insufficient variance for inclusion in the model.

D. Data Collection Procedure

Prior to the main survey, the instruments were validated through two pilot studies. Reliability and sampling adequacy were evaluated using Cronbach's alpha, Kaiser–Meyer–Olkin (KMO) statistics, and Bartlett's test of sphericity. All results met commonly accepted thresholds (Cronbach's alpha > 0.70; KMO > 0.75; Bartlett's test $p < 0.001$), confirming suitability for large-scale administration.

The main survey was conducted between April and June 2025. Questionnaires were administered by participating teachers, who used online questionnaires through Google Forms in schools with adequate computer facilities and distributed paper-based questionnaires in schools with limited technological infrastructure; responses collected on paper were subsequently entered into the online database by the research team. Students completed the questionnaire during supervised classroom sessions, while teachers provided technical assistance when necessary. Teacher questionnaires were administered separately to minimize response bias. Participation across Grades 3, 4, and 5 was monitored throughout data collection in order to maintain a balanced distribution of respondents across grade levels.

E. Ethical Approval and Informed Consent

This study involved human participants and adhered to general ethical standards for educational research. The survey was non-interventional in design: no educational intervention or experimental treatment was administered to participants. Participation was voluntary, and respondents were briefed on the study's purpose before completing the survey. Students could decline to participate or omit any item they preferred not to answer, without penalty. Data collection was carried out with the cooperation of participating schools and teachers, and all data were used exclusively for research purposes. Students were assured that participation would not affect their academic standing or teacher evaluation of their performance.

Formal approval from an institutional review board or ethics committee was not obtained, as such approval was not required for non-interventional educational surveys of this kind under institutional practice at the time of data collection. No personally identifiable data were collected, and all responses were anonymized in full prior to analysis.

F. Data Analysis

Data were analyzed using IBM SPSS 20 and SmartPLS 3.2.9. The final sample size of 4403 students exceeded the minimum requirements for PLS-SEM analysis. According to the "10-times rule", the sample size should be at least ten times the maximum number of structural paths directed at any latent construct [29], indicating that the dataset provided sufficient statistical power.

The analysis was conducted in two stages: evaluation of the measurement model and evaluation of the structural model.

Because DCCC was specified as a second-order construct comprising the six first-order dimensions described in the conceptual framework (INT, SHR, ENG, COL, NET, and MDI), it was estimated using the two-stage (disjoint two-stage) approach: latent variable scores for the six first-order dimensions were first obtained from a lower-order measurement model, and these scores then served as indicators of the second-order DCCC construct in a separate higher-order model—a procedure consistent with established recommendations for specifying reflective higher-order constructs in PLS-SEM [29]. Environmental Factors (EF) were retained as a reflective construct measured by three indicators capturing family support for technology use at home, classroom technological infrastructure, and teachers' digital competence; although these conditions are conceptually distinct, they were treated as co-occurring features of a broader environment of digital-education readiness, consistent with the Person–Environment Interaction and ecological perspectives that ground the study's conceptual framework [4, 5]. The measurement model was evaluated for indicator reliability, construct reliability, convergent validity, and discriminant validity. Indicator reliability was assessed using outer loadings, while construct reliability was evaluated through Cronbach's alpha and composite reliability (CR). Convergent validity was examined using the average Variance Extracted (AVE), and discriminant validity was assessed using the Fornell–Larcker criterion and the Heterotrait–Monotrait Ratio (HTMT) [29, 30].

The structural model evaluation included the analysis of path coefficients, Coefficients of determination (R^2), and Effect sizes (f^2). Predictive relevance was examined using the Stone–Geisser Q^2 statistic and the PLSpredict procedure. Q^2 was obtained through the blindfolding procedure with an

omission distance of $D = 7$, which omits and re-estimates portions of the data to evaluate the model's out-of-sample predictive relevance for each key endogenous construct, with values above zero indicating predictive relevance [29]. PLSpredict was applied using $k = 10$ folds and 10 repetitions, generating out-of-sample predictions for the indicators of the key endogenous constructs and enabling the model's predictive power to be benchmarked against a naive linear-regression-model baseline [29]. The significance of direct and indirect relationships was tested using a bootstrapping procedure with 5000 resamples.

Prior to conducting MGA, measurement invariance of the composite models was assessed using the MICOM procedure, which assesses measurement equivalence across groups before structural relationships are compared. MICOM proceeds in three steps: configural invariance, which confirms that the same indicators, algorithm settings, and model specifications are applied across groups; compositional invariance, which employs a permutation-based test of the correlation between group-specific composite scores to verify that composites are formed equivalently across groups; and equality of composite means and variances. Attaining at least compositional invariance is a precondition for validly comparing structural path coefficients across groups, as unmet invariance could mean that observed differences reflect measurement artifacts rather than genuine structural differences among constructs [29, 31]. MICOM was therefore applied to each pair of groups examined in the subsequent MGA. MGA was subsequently performed to compare structural relationships across gender, grade level, and residential groups. These three grouping variables were selected because each corresponds to a background characteristic that, as established in the study's conceptual framing, may shape students' opportunities to develop digital competence: grade level captures developmental variation in cognitive maturity and cumulative exposure to digital tools across the primary-school years; gender represents a dimension along which digital-competence research has commonly examined differential patterns of technology engagement; and area of residence captures contextual variation in digital infrastructure, family resources, and educational support across Vietnam's diverse regions. Comparing the EF–IF–DCCC structural relationships across these groups therefore allows the study to examine whether the same environmental and individual pathways to DCCC operate consistently for students with different developmental profiles, backgrounds, and contextual circumstances.

V. Result and Discussion

A. Preliminary Analysis

Prior to estimating the PLS-SEM model, the dataset was examined to verify data quality and suitability for structural modelling. Data were gathered via electronic and paper-based questionnaires. After data cleaning and removal of incomplete responses, 4403 valid student responses were included in the final analysis.

Outliers were identified using boxplots and standardized z-scores. Minor deviations were observed in several NET and MDI indicators; however, all values remained within acceptable thresholds ($|z| < 3$), indicating no severe outliers. Data distribution was examined using skewness and kurtosis statistics. All indicators fell within recommended limits ($|\text{Skew}| < 2$; $|\text{Kurtosis}| < 7$), consistent with approximate normality.

Multicollinearity and common method bias were evaluated using Variance Inflation Factor (VIF) values. All independent variables showed VIF values below 1.30, well under the conservative threshold of 3.3 [32], suggesting no multicollinearity issues and a low risk of common method bias.

Overall, the dataset satisfied the requirements for structural equation modelling. The summary results are presented in Table 1.

Table 1. Preliminary data checks: Distribution, outliers and common method bias

Indicator/Statistic	Result/Value
Outliers (Boxplot, z-score)	Minor deviations in NET1–NET3, MDI2–MDI3; all $\|z\| < 3$
Skewness	–1.474 to +0.284
Kurtosis	–1.465 to +1.397
Interpretation	No severe outliers; data approximately normal [29]
VIF range (CMB check)	1.070–1.287
Tolerance	0.785–0.934
Conclusion	No multicollinearity; low risk of common method bias [32]

B. Measurement Model Evaluation

1) Reliability and convergent validity

The measurement model included three latent constructs: Environmental Factors (EF), Internal Factors (IF), and Digital Communication and Collaboration Competence (DCCC).

All indicators demonstrated acceptable outer loadings (>0.58). IF indicators showed the highest loadings (0.838), while EF indicators ranged from 0.580 to 0.767, which are acceptable for exploratory research.

Construct reliability was examined using Cronbach's alpha, rho_A, and Composite Reliability (CR). CR values for EF, IF, and DCCC were 0.713, 0.825, and 0.892, respectively, exceeding the recommended threshold of 0.70. For EF, by contrast, Cronbach's alpha (0.435) and rho_A (0.438) did not reach the conventional 0.70 threshold—a pattern attributable largely to the construct's small number of indicators ($k = 3$) and the unequal loadings across them (0.580–0.767), conditions under which alpha is known to underestimate true reliability; composite reliability, which weights indicators by their actual loadings and is generally regarded as the more appropriate index in variance-based structural equation modeling, nonetheless reached an acceptable level (0.713) [29]. IF's Cronbach's alpha (0.576) was likewise modest; because IF is measured with only two indicators—a configuration for which alpha is known to be a conservative estimate—its composite reliability (0.825) and AVE (0.702) remain the more informative indices, and both are well above recommended thresholds.

Convergent validity was evaluated using the Average Variance Extracted (AVE), which ranged from 0.456 to 0.702. The AVE value for EF (0.456), however, fell slightly below the conventional 0.50 threshold—a result that should be interpreted with caution, since AVE is an unweighted

average of squared loadings and is therefore disproportionately influenced by the comparatively lower-loading indicator (TEACH_SKILL) within a three-indicator construct. Despite this shortfall, EF was retained in its current form based on its theoretical relevance to the proposed EF–IF–DCCC model, together with its acceptable composite reliability and significant, statistically supported loadings, and its discriminant validity met recommended criteria [29, 31].

Taken together, these results indicate that the measurement model is broadly adequate to support the structural analyses that follow: DCCC and IF demonstrated strong reliability and convergent validity overall (IF's comparatively modest Cronbach's alpha being attributable to its two-indicator structure rather than to a substantive weakness), whereas EF—although it satisfied the composite-reliability and discriminant-validity criteria most often regarded as diagnostic in variance-based structural equation modeling—exhibited a convergent-validity profile that fell short of conventional thresholds and is acknowledged as a limitation of the measurement model rather than a fully resolved property (Table 2).

Table 2. Reliability and convergent validity of the measurement model

Latent Construct	Indicator	Outer Loading	Cronbach's α	rho_A	CR	AVE
EF	CLASS_EQUIP	0.666	0.435	0.438	0.713	0.456
	TEACH_SKILL	0.580				
	HOME_SUPPORT	0.767				
IF	LEARN_FEEL	0.838	0.576	0.576	0.825	0.702
	LEARN_USE	0.838				
DCCC (HOC)	COL	0.831	0.854	0.864	0.892	0.581
	ENG	0.811				
	INT	0.774				
	MDI	0.674				
	NET	0.668				
	SHR	0.798				

Abbreviations: EF = Environmental Factors; IF = Internal Factors; DCCC = Digital Communication and Collaboration Competence; CR = Composite Reliability; AVE = Average Variance Extracted.

2) Discriminant validity

Discriminant validity was examined using the Fornell–Larcker criterion and the Heterotrait–Monotrait Ratio (HTMT).

The Fornell–Larcker criterion was satisfied, as the square root of AVE for each construct (DCCC = 0.762; EF = 0.675; IF = 0.838) exceeded inter-construct correlations.

All HTMT values fell below the 0.85 threshold, confirming strong discriminant validity.

Cross-loading analysis additionally confirmed that each indicator loaded most strongly on its intended construct. The detailed results are provided in Tables 3 and 4, with full cross-loadings presented in Table A1.

Table 3. Discriminant validity: Fornell–Larcker matrix

Construct	DCCC	EF	IF
DCCC	**0.762**	-	-
EF	0.358	**0.675**	-
IF	0.445	0.375	**0.838**

Table 4. Heterotrait–Monotrait Ratios (HTMT)

Construct Pair	HTMT
DCCC–EF	0.570
DCCC–IF	0.626
EF–IF	0.694

3) Validated measurement model

All indicators showed statistically significant standardized loadings ($p < 0.001$). The six first-order dimensions of DCCC demonstrated strong relationships with the higher-order construct, with loadings ranging from 0.668 to 0.831.

These findings confirm that the six dimensions collectively represent a coherent construct of DCCC among primary school students. The validated measurement model is illustrated in Fig. 2.

Overall, the validated measurement model comprises three latent constructs—Environmental Factors (EF), Internal Factors (IF), and Digital Communication and Collaboration Competence (DCCC)—together with the six first-order dimensions through which DCCC, specified as a higher-order construct, is represented. All standardized loadings across the model were statistically significant ($p < 0.001$), indicating that each indicator and first-order dimension contributed meaningfully to its respective construct. The six first-order dimensions of DCCC (INT, SHR, ENG, COL, NET, and MDI) exhibited moderate to strong loadings on the higher-order construct, ranging from 0.668 to 0.831, indicating that each dimension contributed meaningfully, in varying degrees, to the overall DCCC construct. IF indicators displayed particularly strong loadings (0.838 for both LEARN_FEEL and LEARN_USE), consistent with the construct's high composite reliability and convergent validity reported above, whereas EF indicators, while acceptable (ranging from 0.580 to 0.767), were comparatively weaker—a pattern consistent with the construct's measurement profile discussed earlier in this subsection. Fig. 2 depicts this validated structure graphically, illustrating how the observed indicators converge on their respective first-order constructs (EF, IF, and the six DCCC dimensions) and how these, in turn, converge on the higher-order DCCC construct, thereby offering readers a visual confirmation that the measurement model provides a coherent, empirically supported basis for the structural analysis that follows.

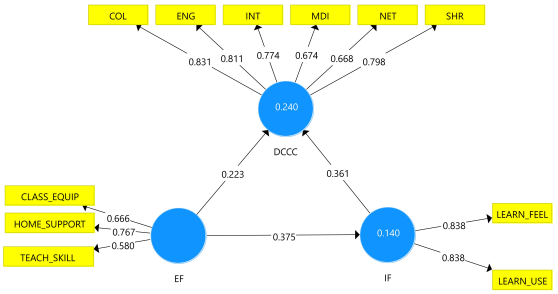


Fig. 2. Validated measurement model with standardized loadings.

C. Structural Model Evaluation

1) Collinearity assessment

Collinearity diagnostics indicated no issues. Outer VIF values ranged from 1.03 to 2.17, and inner VIF values ranged from 1.00 to 1.16, all below the threshold of 5.0. Detailed results are presented in Tables A2 and A3.

2) Hypothesis testing

The structural model results revealed that EF had a significant positive effect on IF (β = 0.375, p < 0.001), supporting H1. EF also had a direct positive effect on DCCC (β = 0.223, p < 0.001), supporting H2. IF significantly influenced DCCC (β = 0.361, p < 0.001), supporting H3. H4—which proposed that EF exerts an indirect influence on DCCC through IF—was supported: the mediation analysis indicated a statistically significant indirect relationship between EF and DCCC via IF (β = 0.135, p < 0.001), consistent with a pattern of partial mediation. These results are summarized in Table 5.

Table 5. Results of hypothesis testing

Hypothesis	Relationship	Path Coefficient (β)	p-value	Conclusion
H1	EF → IF	0.375	p < 0.001	Supported
H2	EF → DCCC	0.223	p < 0.001	Supported
H3	IF → DCCC	0.361	p < 0.001	Supported
H4	EF → IF → DCCC	0.135	p < 0.001	Supported

3) Model explanatory power

The model demonstrated moderate explanatory power. EF accounted for 14% of the variance in IF (R^2 = 0.14), while EF and IF together accounted for 24% of the variance in DCCC (R^2 = 0.24). While these values reflect a moderate explanatory capability consistent with patterns typically observed in survey-based behavioural PLS-SEM research, they also indicate that a substantial proportion of the variance in both IF (approximately 86%) and DCCC (approximately 76%) was not accounted for by the constructs examined here. EF and IF therefore represent meaningful, but not exhaustive, explanations of students' digital communication and collaboration competence, and the model should be regarded as a partial account of the variability in these outcomes rather than a comprehensive one.

Effect size analysis indicated that EF → IF (f^2 = 0.163) and IF → DCCC (f^2 = 0.148) had medium effects, whereas EF → DCCC (f^2 = 0.056) had a small effect, according to commonly used effect size benchmarks [33]. These results are presented in Table 6.

Predictive relevance of the structural model was further evaluated using Stone–Geisser's Q^2 statistic, obtained through the blindfolding procedure with an omission distance of D = 7, which omits and re-estimates portions of the data to evaluate the model's out-of-sample predictive capacity for each endogenous construct. Both endogenous constructs returned positive Q^2 values for construct cross-validated redundancy (Q^2 = 0.138 for DCCC; Q^2 = 0.097 for IF), confirming that the structural model possesses predictive relevance for both outcomes [29]. Out-of-sample predictive power was further examined using the PLSpredict procedure (k = 10 folds, 10 repetitions), which compares the PLS-SEM model's prediction errors against those of a naïve linear-regression-model (LM) benchmark [29]. At the construct level, both DCCC (Q^2_predict = 0.127) and IF (Q^2_predict = 0.140) exhibited positive predictive relevance, indicating that the model's explanatory structure translates into out-of-sample predictive capability. At the indicator level, however, the PLS-SEM model's prediction errors (RMSE, MAE) were higher than those of the LM benchmark for the majority of the indicators of both constructs, with differences that were uniformly small in magnitude; following established classification criteria, this pattern indicates comparatively low predictive power at the indicator level. Taken together, these results suggest that the model demonstrates meaningful predictive relevance at the construct level, while its indicator-level out-of-sample performance remains closely comparable to that of a simple linear benchmark—a pattern frequently encountered in survey-based behavioural models with moderate explanatory power, and one that should be interpreted as a boundary condition on generalizability rather than as evidence against the structural relationships identified.

Table 6. Model explanatory power (R^2 and f^2)

Dependent Variable	Independent Variable	R^2	f^2	Effect Size
IF	EF	0.140	0.163	Medium
DCCC	EF	0.240	0.056	Small
DCCC	IF	0.240	0.148	Medium

4) Mediation analysis

Mediation analysis showed that EF had both direct (β = 0.223, p < 0.001) and indirect effects on DCCC through IF (β = 0.135, p < 0.001), resulting in a total effect of β = 0.358. These findings indicate partial mediation, supporting H4 and suggesting that IF may act as an intermediating pathway through which environmental conditions relate to students' digital communication and collaboration competence (Table 7).

Table 7. Mediation analysis

Relationship	Direct Effect	p	Indirect Effect	p	Total Effect	Mediation Type
EF → IF → DCCC	0.223	<0.001	0.135	<0.001	0.358	Partial mediation

5) Multi-group analysis

Because valid comparison of structural relationships across groups requires that the underlying constructs are measured equivalently, measurement invariance was assessed via MICOM before MGA was conducted. Configural invariance was established by design, as the same indicators, data treatment, and algorithm settings were applied across all groups. Compositional invariance (Step 2, permutation-based) was subsequently evaluated for each construct across all group-pair comparisons: IF achieved full invariance in 8 of 10 comparisons, EF in 5 of 10, and DCCC in 3 of 10, with the largest departure observed for EF between the Remote and Metropolitan urban groups (c = 0.664 against a threshold of 0.964). All three constructs achieved full compositional invariance for the Grade 3 vs Grade 5 comparison (DCCC c = 0.999, p = 0.111; EF c = 1.000, p = 0.986; IF c = 0.9998, p = 0.518), which supports confident interpretation of the corresponding grade-level MGA findings reported below. Where partial invariance was

found—mainly for EF- and DCCC-related paths in regional comparisons involving the Remote group—the corresponding MGA results are interpreted with appropriate caution.

Multi-group analysis revealed no significant gender differences across the structural relationships. The detailed results are presented in Table 8.

Table 8. Multi-group analysis by gender

Comparison	Path	Δβ	P	Conclusion
Female vs Male	EF → DCCC	–0.0216	0.470	No difference
Female vs Male	EF → IF	–0.0036	0.903	No difference
Female vs Male	IF → DCCC	+0.0252	0.349	No difference

Significant differences were observed across grade levels, particularly between Grade 3 and Grade 5 in the relationships EF → IF and IF → DCCC. The detailed results are presented in Table 9.

Table 9. Multi-group analysis by grade level

Grade Pair	Path	Δβ	p	Conclusion
Grade 3 vs Grade 4	EF → DCCC	–0.0373	0.302	No difference
Grade 3 vs Grade 4	EF → IF	–0.0527	0.143	No difference
Grade 3 vs Grade 4	IF → DCCC	–0.0471	0.163	No difference
Grade 4 vs Grade 5	EF → DCCC	+0.0594	0.089	No difference
Grade 4 vs Grade 5	EF → IF	–0.0360	0.284	No difference
Grade 4 vs Grade 5	IF → DCCC	–0.0593	0.067	No difference
Grade 3 vs Grade 5	EF → IF	–0.0887	0.019	Difference ($p < 0.05$)
Grade 3 vs Grade 5	IF → DCCC	–0.1064	0.003	Difference ($p < 0.01$)
Grade 3 vs Grade 5	EF → DCCC	+0.0221	0.561	No difference

As shown in Table 9, the EF → IF and IF → DCCC paths were stronger among Grade 5 students than Grade 3 students ($\Delta\beta = -0.089$, $p = 0.019$ and $\Delta\beta = -0.106$, $p = 0.003$, respectively). Because full compositional invariance was confirmed for this comparison, the difference is unlikely to stem from measurement non-equivalence; it may instead be associated with developmental maturity and cumulative exposure to digital technologies among older students, although the cross-sectional design does not permit causal conclusions.

Regional differences were more pronounced, with significant variations mainly in EF → IF and IF → DCCC relationships. These findings suggest that contextual disparities shape digital competence development. The detailed regional comparison results are presented in Table 10 and are discussed below. The largest regional difference occurred between the Remote and Metropolitan urban groups for EF → IF ($\Delta\beta = +0.242$, $p < 0.001$); the Provincial urban–Metropolitan urban comparison also differed significantly in EF → IF ($\Delta\beta = +0.166$) and IF → DCCC ($\Delta\beta = +0.097$). These patterns may relate to disparities in technology access, family and school support, and learning environments across residential settings. Because compositional invariance for EF and DCCC was not fully established in most regional pairs—especially those involving the Remote group (e.g., EF $c = 0.664$ for Remote vs. Metropolitan urban)—such comparisons warrant cautious interpretation, whereas the Provincial urban–Metropolitan urban EF → IF result, which met full compositional invariance, can be read with greater confidence.

Table 10. Multi-group analysis by region

Region Pair	Path	Δβ	p	Conclusion
Remote area vs Rural area	EF → IF	+0.0976	0.021	Difference ($p < 0.05$)
	EF → DCCC	+0.0823	0.060	No difference
	IF → DCCC	–0.0785	0.061	No difference
Remote area vs Provincial urban area	EF → IF	+0.0769	0.070	No difference
	EF → DCCC	+0.0046	0.919	No difference
	IF → DCCC	–0.0414	0.343	No difference
Remote area vs Metropolitan urban area	EF → IF	+0.2425	<0.001	Strong difference
	EF → DCCC	+0.0428	0.377	No difference
	IF → DCCC	+0.0552	0.236	No difference
Rural area vs Provincial urban area	EF → IF	–0.0207	0.580	No difference
	EF → DCCC	–0.0777	0.044	Difference ($p < 0.05$)
	IF → DCCC	+0.0370	0.298	No difference
Rural area vs Metropolitan urban area	EF → IF	+0.1449	<0.001	Strong difference
	IF → DCCC	+0.1337	<0.001	Strong difference
	EF → DCCC	–0.0395	0.348	No difference
Provincial urban area vs Metropolitan urban area	EF → IF	+0.1656	<0.001	Strong difference
	IF → DCCC	+0.0966	0.015	Difference ($p < 0.05$)
	EF → DCCC	+0.0382	0.368	No difference

The final structural model is presented in Fig. 3. As illustrated in Fig. 3, the three significant structural paths of the final model are: EF → IF ($\beta = 0.375$, $p < 0.001$), EF → DCCC ($\beta = 0.223$, $p < 0.001$), and IF → DCCC ($\beta = 0.361$, $p < 0.001$). The model explained 14% of the variance in IF ($R^2 = 0.14$) and 24% of the variance in DCCC ($R^2 = 0.24$). Consistent with the partial mediation pattern discussed in the Mediation Analysis subsection, both a direct path (EF → DCCC) and an indirect path (EF → IF → DCCC, $\beta = 0.135$, $p < 0.001$) are present, indicating that IF represents one pathway through which environmental conditions are associated with students' digital communication and collaboration competence.

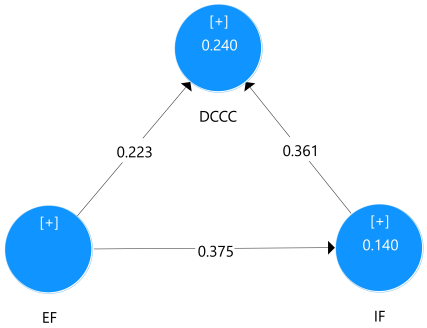


Fig. 3. Final structural model with significant paths.

D. Teacher Perspectives on Factors Influencing DCCC

To complement the structural analysis of the student data, descriptive ratings from the 918 participating teachers were examined. Teachers rated, on a five-point scale (0 = no influence to 4 = very strong influence), the extent to which seven factors influence students' DCCC. School technological infrastructure ($M = 2.33$) and family support for technology use ($M = 2.30$) were rated as the most influential factors, followed by teachers' own digital skills and teaching methods ($M = 2.17$) and students' attitudes and experience with technology ($M = 2.09$). Background factors were rated as comparatively less influential, with region of residence in an intermediate position ($M = 1.99$), and student

age (M = 1.69) and gender (M = 1.26; 56.8% of teachers reported "no" or "little" influence) rated as the least influential.

This pattern of teacher-rated influence is broadly consistent with the structural and multi-group findings reported above. The three factors teachers rated as most influential—classroom infrastructure, family support, and teachers' own digital skills—correspond to the three EF sub-dimensions that the structural model identified as significant predictors of IF and DCCC, while teachers' comparatively lower rating of students' attitudes and experience is aligned with the smaller, though still significant, direct role of IF. Among the background factors, teachers' ranking of gender as least influential converges with the absence of significant gender differences in the MGA (Table 8), their higher rating of region provides contextual corroboration for the larger number of significant regional differences identified (Table 10), and their intermediate rating of age corresponds to the more limited pattern of grade-level differences (Table 9). Taken together, these correspondences offer complementary practitioner perspectives on the student-based findings rather than independent statistical confirmation of the structural relationships. Because the teacher data were used descriptively and interpretively—and were not incorporated into the structural model—they serve a triangulation/contextualization role rather than a model-testing role.

E. Discussion

The results of this study provide empirical evidence for the relationships among Environmental Factors (EF), Internal Factors (IF), and primary students' Digital Communication and Collaboration Competence (DCCC). Overall, the findings indicate that both contextual conditions, including ICT-supported learning environments, digital platforms, and collaborative tools, and students' internal learning processes are linked to digital communication and collaboration competence. The EF–IF–DCCC model demonstrated moderate explanatory power, supporting the view that digital competence emerges from the interaction between environmental opportunities and learners' engagement with digital technologies rather than from technological access alone [1, 26]. Whereas much of the existing literature has examined environmental and internal influences on digital competence separately, or has considered only limited aspects of digital competence, the present study brings environmental factors, internal factors, and a multidimensional conceptualization of DCCC together within a single explanatory framework, offering a more integrated account of how these elements relate to one another.

The results show that EF significantly influence IF, supporting Hypothesis 1. This finding suggests that ICT infrastructure, digital platforms, teachers' digital competence, and family support may be associated with students' attitudes, confidence, and engagement with digital technologies. Previous research similarly indicates that access to digital resources and supportive learning environments has been linked to learners' motivation and attitudes toward technology use [16]. In addition, teachers' ability to integrate digital tools into instructional practices has been shown to enhance students' engagement with digital learning activities [25, 34]. Family environments also play a critical role, as parental support and positive attitudes toward technology strengthen children's confidence and motivation in using digital tools [7, 10]. These findings align with prior research examining the role of family and home digital environments in supporting children's digital literacy development [35]. These findings are consistent with ecological perspectives, which emphasize that learning outcomes are associated with the interactions between individuals and their environments [4]. Beyond confirming that these associations exist, it is worth considering why supportive environments may be linked to stronger internal engagement in this way: well-equipped classrooms, digitally competent teachers, and encouraging family attitudes plausibly lower the practical and psychological barriers that might otherwise discourage young learners from engaging with digital tools, creating conditions in which curiosity, confidence, and sustained interest are more likely to develop. Viewed this way, environmental conditions may function less as a direct source of competence than as a backdrop that makes positive engagement with technology more attainable for students at this age.

The findings also confirm that EF are significantly associated with DCCC, supporting Hypothesis 2. This result indicates that contextual conditions are associated not only with internal learning processes but also, more directly, with students' communication and collaboration skills in technology-enhanced and platform-based learning environments. Previous studies show that technology-enhanced learning environments facilitate communication and collaboration when digital tools are integrated into meaningful learning activities [13, 18]. In particular, cloud-based collaborative tools have been shown to enhance students' teamwork, communication, and engagement by enabling real-time interaction, shared workspaces, and continuous feedback [21]. In primary education, access to structured digital learning opportunities has been found to strengthen students' interaction and collaboration skills [20]. Furthermore, teachers' digital competence and pedagogical practices play a key role, as the integration of digital tools into classroom activities encourages students to participate in online discussions, shared tasks, and collaborative problem-solving [9, 25]. These results align with digital competence frameworks emphasizing that communication and collaboration skills develop through active participation in digital learning environments [1]. This direct association may correspond with the fact that environments rich in digital infrastructure and structured opportunities for technology-supported interaction give students more frequent occasions to practice communication and collaboration in authentic, technology-mediated settings—opportunities that, over time, may help explain why such conditions relate not only to students' attitudes and confidence but also, more directly, to the communication and collaboration competencies those attitudes and confidence are meant to support.

The results further indicate that IF significantly influence DCCC, supporting Hypothesis 3. This finding highlights the role of learners' psychological engagement with digital

technologies and its association with digital competence. This is consistent with prior findings indicating that self-efficacy and motivation are associated with students' engagement, critical thinking, and learning performance in technology-mediated learning contexts. Research on digital literacy consistently emphasizes that students who hold greater confidence and more positive attitudes toward digital technologies tend to exhibit stronger digital skills and collaborative capabilities [15, 20]. This is also consistent with self-regulated learning theory, which underscores the role of motivation and engagement in learning outcomes [5]. In ICT-supported learning environments, students who actively engage with digital tools and platforms are more likely to develop communication and collaboration skills required for technology-supported learning. This relationship may be understood by considering what communication and collaboration in digital settings actually require of a learner moment to moment: initiating contact, sharing ideas, responding to peers, and persisting through technical or social friction. Each of these is closely tied to a student's willingness to engage and their confidence that engagement will go reasonably well. Students who approach digital tools with greater confidence and positive attitudes may therefore be more inclined to take the kinds of small, repeated interactional risks—asking a question online, offering an idea in a shared workspace, persisting after a misunderstanding—that, cumulatively, correspond with stronger communication and collaboration competence. It is also worth noting that, of the three structural paths examined, the path from internal factors to DCCC (β = 0.361) was numerically stronger than the direct path from environmental factors to DCCC (β = 0.223). Read cautiously, this pattern may correspond with a difference in how proximal each set of factors is to the competence being measured: environmental conditions—infrastructure, teacher support, family attitudes—primarily structure the opportunities and circumstances under which digital learning can occur, whereas internal factors such as attitudes, confidence, and engagement sit closer to the moment-to-moment behaviors through which communication and collaboration competence is actually enacted. On this reading, environmental conditions may matter most through the internal orientations that, in turn, are more directly linked to how competence is expressed in practice—a reading that is consistent with, and may help explain, the partial-mediation pattern discussed below.

The mediation analysis indicates that IF partially mediate the relationship between EF and DCCC. This finding suggests that technological resources alone do not automatically correspond with digital competence. Instead, environmental conditions appear associated with competence both directly and indirectly through students' attitudes, confidence, and learning experiences with digital technologies. Examining the EF → IF, EF → DCCC, and IF → DCCC pathways within a single explanatory model offers evidence of how contextual and internal factors are associated with one another and with DCCC, an association that would remain only partially visible if each pathway were considered separately. This pattern is consistent with conceptual models of digital competence development proposed in frameworks such as DigComp and UNESCO's digital literacy framework, which highlight the interplay between technological environments and learners' engagement with digital tools [1, 2]. From a technological perspective, this implies that ICT systems and digital learning platforms should be intentionally designed to foster positive user experiences, sustained engagement, and active participation in collaborative learning processes.

Understood within the integrated EF–IF–DCCC framework, this partial-mediation pattern suggests that the relationship between environmental conditions and digital competence is not a single, uniform channel but two distinguishable, complementary routes: a more direct route, in which favorable conditions correspond with stronger competence in their own right, and an indirect route, in which those same conditions appear to operate partly through their association with the attitudes, confidence, and engagement that, this study's results suggest, are themselves more closely linked to competence enactment. Considered together with the relative strength of the IF → DCCC path noted above, this pattern may help explain why environmental investment on its own — without a corresponding link to how students come to feel about and engage with digital technologies—might be associated with comparatively modest gains in competence relative to what an environment-only account would anticipate.

The structural model accounts for a meaningful, if partial, portion of the variance in both internal factors (R^2 = 0.14) and digital communication and collaboration competence (R^2 = 0.24). As the predictive-relevance analyses reported in the Results section indicate, the model demonstrates positive out-of-sample relevance for both endogenous constructs, while indicator-level predictive accuracy remains modest—a pattern that is well-documented in survey-based behavioral research at comparable explanatory scales and that appropriately frames the associations described here as bounded rather than definitive. The portion of variance that remains unexplained may reflect the influence of factors not captured in this model: individual learner differences, peer interaction dynamics, classroom instructional practices, school culture, and broader socioeconomic conditions each represent plausible influences that future research may investigate with designs better suited to estimating their relative contributions. Considered as a whole, the findings are best understood as identifying a set of meaningful associations among environmental conditions, student internal factors, and digital communication and collaboration competence within this Vietnamese primary context—not as a comprehensive account of the phenomenon or as evidence sufficient for strong developmental inference. The cross-sectional design and reliance on self-reported measures accordingly limit interpretation to associations that are consistent with the theoretical framework and that point toward directions for longitudinal and experimental follow-up.

The multi-group analysis provides additional insights into demographic differences. The absence of significant gender differences is consistent with digital competence showing similar patterns of association among male and female students. However, differences across grade levels indicate that the associations involving internal learning factors appear stronger among students with greater experience with

digital learning activities. Regional differences further highlight disparities in access to digital infrastructure and learning opportunities, consistent with research documenting inequalities in digital access across educational contexts [36].

The grade-level pattern warrants closer examination. The significant differences on both the EF → IF and IF → DCCC pathways between Grade 3 and Grade 5 students—alongside the absence of a significant EF → DCCC difference across the same comparison—may correspond with differences in how students at different points in primary schooling engage with school-based digital tools and connect environmental conditions to competence-relevant practice. Students in Grade 5 may have built up greater exposure to technology-supported classroom routines than students in Grade 3, and this additional experience may be associated with a stronger tendency to translate environmental affordances into active internal engagement and, from there, into the communicative and collaborative behaviors that constitute digital competence; students in Grade 3, who may have had fewer opportunities to engage with these routines, may exhibit a comparatively weaker associative pattern between environmental context, internal orientation, and observable competence. The stability of the EF → DCCC path across grade levels may further suggest that direct links between environmental conditions and competence outcomes are relatively stable across primary-school years, while the mediated route through internal factors appears more sensitive to accumulated experience with school-based technology use. That full compositional invariance was established for all three constructs in the Grade 3–Grade 5 comparison provides methodological support for treating these observed differences as substantively meaningful rather than as measurement artefacts.

The regional variation in structural path strengths warrants similarly careful consideration. The pattern in which EF → IF and, in several comparisons, IF → DCCC associations appear stronger in metropolitan and provincial urban areas than in rural or remote areas may correspond with differences in the opportunity structures and learning environments available across these residential contexts—including the breadth and consistency of digital infrastructure in schools, the availability of technology-equipped classrooms and trained educators, and the extent to which families can support technology-enabled learning at home. Viewed through this lens, the observed regional differences may reflect variation in the conditions that enable students to develop and exercise the attitudes, engagement, and competence this study examines, rather than inherent differences in the capacities or dispositions of students themselves. Given that measurement invariance was not equally established across all regional comparisons—particularly for the EF construct in comparisons involving remote areas—those findings should be interpreted with appropriate caution. Nonetheless, the regional pattern overall may suggest that digital education initiatives could benefit from attending to differences in local learning conditions, particularly in settings where infrastructure and resource access may limit the opportunities available to students for meaningful technology-supported participation.

From a design perspective, the findings suggest that digital collaborative learning environments should be intentionally structured to promote interaction and active participation. Learning activities supported by digital platforms should incorporate collaborative tasks, peer interaction, and shared problem-solving to support students' communication and collaboration skills.

From a technological perspective, the results indicate that digital platforms, online learning systems, and collaborative tools should be designed not only to provide access to content but also to facilitate meaningful interaction among learners. Empirical evidence also suggests that features such as real-time collaboration, shared digital workspaces, and feedback mechanisms play a crucial role in enhancing student engagement and effective contribution in collaborative learning environments [21].

Considered together, these findings position the study's contribution less in indicating that environmental and internal factors each relate to digital competence—prior research has separately suggested as much—than in examining EF, IF, and DCCC within a single explanatory framework and offering evidence of how contextual and internal factors are associated with one another and with DCCC across the EF → IF, EF → DCCC, and IF → DCCC pathways considered here. This integrated perspective is reinforced by conceptualizing DCCC as a multidimensional, second-order construct spanning interaction, sharing, digital citizenship, collaboration, netiquette, and management of digital presence and identity, which lends a degree of conceptual clarity and measurement precision to the study of DCCC among primary-age learners. Generating this evidence from a large sample of primary school students drawn from 21 provinces of Vietnam—a population, developmental stage, and national setting in which such integrated evidence remains comparatively limited—extends the range of contexts in which these relationships have been examined. The descriptive convergence between teachers' perceptions of influential factors and the patterns identified in the student-based model, reported above, offers further contextual corroboration for these findings from an independent practitioner perspective.

Overall, this study extends existing research by providing a more integrated explanation of digital competence development among primary school students, emphasizing the importance of both contextual conditions and learners' engagement within technology-enhanced learning environments.

VI. Conclusion

This study provides empirical evidence on associations between Environmental Factors (EF), Internal Factors (IF), and Digital Communication and Collaboration Competence (DCCC) among primary school students. The findings show that EF was positively associated with both IF and DCCC, that IF was positively associated with DCCC, and that IF partially mediated the EF–DCCC relationship—consistent with a dual-pathway model in which contextual conditions are linked to digital competence both directly and through students' engagement, confidence, and attitudes toward digital technologies.

Environmental factors—including technological infrastructure, family support, and teachers' digital

competence—were associated with DCCC both directly and indirectly through students' attitudes, confidence, and learning experiences. In particular, the partial mediation through internal factors suggests that the correspondence between ICT-supported learning environments and student digital competence may be linked to how learners engage with and participate in technology-enhanced activities.

By integrating EF and IF as complementary predictors of a multidimensional conceptualization of DCCC, this study advances an empirically grounded framework applicable to primary education settings. Grounded in a large-scale sample from diverse Vietnamese educational contexts, the findings support the value of considering both environmental conditions and students' internal engagement alongside access to digital technologies—while acknowledging that the model accounts for a limited portion of variance in digital competence outcomes (R^2 = 0.14 for IF; R^2 = 0.24 for DCCC).

From a technological perspective, the study underscores the need to design digital learning systems that facilitate interaction, collaboration, and active participation. ICT platforms, online learning environments, and collaborative tools should be structured to support communication processes and shared learning experiences rather than functioning solely as content delivery mechanisms.

Developmental stage and regional context also emerged as meaningful influences on digital competence. The stronger EF → IF and IF → DCCC relationships observed among older students suggest that digital learning experiences may become increasingly meaningful as students accumulate experience with technology-supported learning activities. Likewise, the regional differences identified in the MGA highlight the continuing importance of contextual conditions, including access to digital infrastructure, family support, and school resources. These findings suggest that digital education initiatives may prove more effective when designed in response to students' developmental readiness and local contextual conditions, rather than applied through a single uniform approach.

The present study employed a cross-sectional design in which all data were gathered at a single point in time. This enables examination of the associations among environmental factors, internal factors, and digital communication and collaboration competence, but does not permit causal or developmental conclusions to be drawn. Future research employing longitudinal designs would enable a more direct examination of how these constructs relate over time and whether the observed associations remain stable as students progress through primary schooling.

All measures were based on participant self-report, meaning that student responses reflect perceived rather than directly observed engagement, attitudes, and competence. Self-reported data may not fully capture actual digital behaviors and practices, and discrepancies between perception and behavior are a recognized limitation of survey-based research in educational technology. Future studies may benefit from incorporating complementary data sources—such as teacher observations, performance-based assessments, or log data from digital learning platforms—alongside self-reported constructs.

The sample was recruited from schools across 21 provinces in Northern, Central, and Southern Vietnam through a purposive school-based strategy designed to achieve broad geographic and contextual diversity, encompassing metropolitan urban, provincial urban, rural, and remote areas. While this approach supports contextual comparisons and provides a large-scale, geographically distributed dataset, the purposive nature of school recruitment means that findings should not be interpreted as nationally representative. Replication with probabilistic sampling designs would strengthen the generalizability of these results to the broader population of primary school students in Vietnam.

Teacher-reported data were included to provide contextual corroboration for the student-based model and to support triangulation of key patterns across informant perspectives. These data were not incorporated into the structural model, as teacher responses reflect perceived influence on a different measurement scale and were not designed as parallel reflective constructs alongside the student-side measures. Future research may benefit from exploring multi-informant or integrated modeling approaches that formally incorporate teacher and school-level factors within a shared analytical framework.

The Environmental Factors (EF) construct demonstrated acceptable Composite Reliability (CR = 0.713) and met discriminant validity criteria, including the Fornell–Larcker criterion and HTMT thresholds. However, the average variance extracted for EF (AVE = 0.456) fell slightly below the conventional 0.50 threshold—a pattern attributable in part to the heterogeneity of the three indicators and the sensitivity of AVE to loading variation within a small indicator set. Findings involving EF-related structural paths are consequently best interpreted with appropriate caution, and future research may benefit from revisiting the operationalization of environmental factors with additional or refined indicators. In particular, because the EF construct combines conceptually distinct dimensions (family support, classroom infrastructure, and teachers' digital competence), future studies may also explore alternative formative or composite specifications of environmental factors and compare their performance with the reflective specification adopted in the present study.

In addition, measurement invariance was evaluated using the MICOM procedure prior to multi-group analysis. While configural and compositional invariance were established for most group comparisons, full invariance was not achieved in all cases. Consequently, certain multi-group comparisons should be interpreted with appropriate caution, and future studies should seek to confirm these findings using samples that allow stronger invariance assessment across groups. Finally, although participation was voluntary and conducted in cooperation with participating schools and teachers, no formal individual parental consent documentation was collected. Given that the study involved minor participants, formal parental or guardian consent procedures represent a stronger form of ethical assurance and should be considered in future research where institutional requirements and study conditions permit.

Building on the limitations identified above, future research may extend and enrich these findings in several

directions. Longitudinal designs would enable examination of how the associations among environmental conditions, internal factors, and digital communication and collaboration competence unfold across primary school years, while mixed-methods approaches incorporating behavioral or performance-based measures of competence would lessen reliance on self-reported data and support convergent validation. Studies employing probabilistic sampling across a wider range of educational contexts—including other national settings—would clarify the generalizability of the EF–IF–DCCC model and help identify whether the relative contributions of environmental and internal factors differ by infrastructure level or cultural context. Multi-informant designs that incorporate independently collected teacher and school-level data alongside student-reported constructs would address the triangulation limitations of the current study and open avenues for multilevel modeling of contextual influences. Methodological focus on the operationalization of the environmental factors construct—including refinement of its factorial structure—would also address construct validity concerns in future applications of this model.

Overall, this study adds to existing scholarship on educational technology and digital competence through large-scale empirical evidence from Vietnamese primary education contexts for an integrated model in which environmental and internal factors are together associated with primary students' digital communication and collaboration competence.

APPENDIX A: CROSS-LOADINGS

Table A1. Cross-loadings of measurement indicators

Indicator	DCCC	EF	IF
CLASS_EQUIP	0.237	**0.666**	0.191
COL	**0.831**	0.299	0.374
ENG	**0.811**	0.257	0.385
HOME_SUPPORT	0.287	**0.767**	0.352
INT	**0.774**	0.295	0.378
LEARN_FEEL	0.381	0.303	**0.838**
LEARN_USE	0.364	0.325	**0.838**
MDI	**0.674**	0.284	0.264
NET	**0.668**	0.264	0.244
SHR	**0.798**	0.243	0.359
TEACH_SKILL	0.187	**0.580**	0.170

Note: Cross-loadings were estimated using the same measurement model as reported in Table 2.

APPENDIX B: MULTICOLLINEARITY DIAGNOSTICS (OUTER AND INNER VIF VALUES)

Table A2. Outer VIF values for measurement indicators

Indicator	Outer VIF
CLASS_EQUIP	1.146
TEACH_SKILL	1.127
HOME_SUPPORT	1.034
LEARN_FEEL	1.196
LEARN_USE	1.196
COL	2.172
ENG	2.133
INT	1.877
MDI	1.681
NET	1.696
SHR	2.132

Table A3. Inner VIF values among latent constructs

Path	Inner VIF
EF → IF	1.000
EF → DCCC	1.163
IF → DCCC	1.163

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

H.H.C. conceptualized the study; H.H.C. and L.T.D. developed the methodology; H.H.C. collected the data; H.H.C. performed the formal analysis; H.H.C. drafted the manuscript; H.H.C. and L.T.D. reviewed and edited the manuscript. Both authors have read and approved the final version of the manuscript.

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REFERENCES

[1] R. Vuorikari, S. Kluzer, and Y. Punie, *DigComp 2.2: The Digital Competence Framework for Citizens—With New Examples of Knowledge, Skills and Attitudes*, EUR 31006 EN, Publications Office of the European Union, Luxembourg (Luxembourg), 2022. doi: 10.2760/115376

[2] N. Law, D. Woo, J. Torre, and G. Wong. (2018). A Global framework of reference on digital literacy skills for indicator 4.4.2. UNESCO. UNESCO Institute for Statistics, Information Paper No. 51. [Online]. Available: https://www.uis.unesco.org/sites/default/files/medias/fichiers/2025/08/ip51-global-framework-reference-digital-literacy-skills-2018-en.pdf

[3] Ministry of Education and Training. (Jan. 2025). Circular No. 02/2025/TT-BGDĐT on the Digital competence framework for learners. [Online]. Available: https://vanban.chinhphu.vn/?pageid=27160&docid=212648

[4] U. Bronfenbrenner, "Ecological models of human development," *International Encyclopedia of Education*, vol. 3, no. 2, pp. 37–43, 1994.

[5] B. J. Zimmerman, "Chapter 2—Attaining Self-Regulation: A Social Cognitive Perspective," in *Handbook of Self-Regulation*, Elsevier, 2000, pp. 13–39. doi: 10.1016/B978-012109890-2/50031-7

[6] O. García-Pérez, M. Inda-Caro, C.-M. Fernández-García, and S. Torío-López, "The influence of perceived family supports and barriers on personal variables in a Spanish sample of secondary school science-technology students," *Int. J. Sci. Educ.*, vol. 42, no. 1, pp. 70–88, Jan. 2020. doi: 10.1080/09500693.2019.1701216

[7] C. Moreno-Morilla, F. Guzmán-Simón, and E. García-Jiménez, "Digital and information literacy inside and outside Spanish primary education schools," *Learn. Cult. Soc. Interact.*, vol. 28, 100455, Mar. 2021. doi: 10.1016/j.lcsi.2020.100455

[8] C. Carboni and S. Main, "Teachers' perceptions of students' ICT skills for online assessments (NAPLAN): Influences and impact," *Issues in Educational Research*, vol. 35, no. 4, pp. 1370–1395, 2025.

[9] D. R. Joshi, K. P. Adhikari, J. Khanal, and S. Belbase, "Impact of digital skills of mathematics teachers to promote students' communication behavior in the classroom," *Contemp. Educ. Technol.*, vol. 15, no. 4, ep454, Oct. 2023. doi: 10.30935/cedtech/13495

[10] S. Bonanati and H. M. Buhl, "The digital home learning environment and its relation to children's ICT self-efficacy," *Learn. Environ. Res.*, vol. 25, no. 2, pp. 485–505, Jul. 2022. doi: 10.1007/s10984-021-09377-8

[11] H. Kuhlemeier and B. Hemker, "The impact of computer use at home on students' internet skills," *Comput. Educ.*, vol. 49, no. 2, pp. 460–480, Sep. 2007. doi: 10.1016/j.compedu.2005.10.004

[12] I. Blau, T. Shamir-Inbal, and O. Avdiel, "How does the pedagogical design of a technology-enhanced collaborative academic course promote digital literacies, self-regulation, and perceived learning of students?" *Internet High. Educ.*, vol. 45, 100722, Apr. 2020. doi: 10.1016/j.iheduc.2019.100722

[13] A. Midtlund, E. J. Instefjord, and A. Lazareva, "Digital communication and collaboration in lower secondary school," *Nordic Journal of Digital Literacy*, vol. 16, no. 2, pp. 65–76, Aug. 2021. doi: 10.18261/issn.1891-943x-2021-02-03

[14] M. Beilmann, S. Opermann, V. Kalmus, J. Vissenberg, and M. Pedaste, "The role of school-home communication in supporting the development of children's and adolescents' digital skills, and the changes brought by COVID-19," *Journal of Media Literacy Education*, vol. 15, no. 1, pp. 1–13, Apr. 2023. doi: 10.23860/JMLE-2023-15-1-1

[15] Z. He, X. Chen, and S. Guo, "Digital competence and its components in basic education," *Interactive Learning Environments*, vol. 32, no. 9, pp. 5174–5185, Oct. 2024. doi: 10.1080/10494820.2023.2211636

[16] C. Audrin and B. Audrin, "Key factors in digital literacy in learning and education: A systematic literature review using text mining," *Educ. Inf. Technol. (Dordr).*, vol. 27, no. 6, pp. 7395–7419, Jul. 2022. doi: 10.1007/s10639-021-10832-5

[17] K. Tzafilkou, M. Perifanou, and A. A. Economides, "Development and validation of students' digital competence scale (SDiCoS)," *International Journal of Educational Technology in Higher Education*, vol. 19, no. 1, 30, Dec. 2022. doi: 10.1186/s41239-022-00330-0

[18] M. Johler, "Collaboration and communication in blended learning environments," *Front. Educ. (Lausanne).*, vol. 7, Oct. 2022. doi: 10.3389/feduc.2022.980445

[19] C.-M. Chen, M.-C. Li, and Y.-T. Chen, "The effects of web-based inquiry learning mode with the support of collaborative digital reading annotation system on information literacy instruction," *Comput. Educ.*, vol. 179, 104428, Apr. 2022. doi: 10.1016/j.compedu.2021.104428

[20] L. Scholes, L. Rowe, K. A. Mills, A. Gutierrez, and E. Pink, "Video gaming and digital competence among elementary school students," *Learn. Media Technol.*, vol. 49, no. 2, pp. 200–215, Apr. 2024. doi: 10.1080/17439884.2022.2156537

[21] Z. Zulpykhar, A. Sadvakassova, Z. Zhalgasbekova, Z. Zhantassova, and A. Kadyrova, "The Role of Cloud-Based Collaborative Tools in Fostering Digital Teamwork and Engagement in Undergraduate Computer Science Courses," *International Journal of Information and Education Technology*, vol. 16, no. 2, pp. 413–421, 2026. doi: 10.18178/ijiet.2026.16.2.2514

[22] L. S. Vygotsky, *Mind in Society: The Development of Higher Psychological Processes*, Cambridge, MA: Harvard University Press, 1978.

[23] L. B. Johanson, T. Leming, B.-H. Johannessen, and T. Solhaug, "Competence in Digital Interaction and Communication—A Study of First-Year Preservice Teachers' Competence in Digital Interaction and Communication at the Start of Their Teacher Education," *The Teacher Educator*, vol. 58, no. 3, pp. 270–288, Jul. 2023. doi: 10.1080/08878730.2022.2122095

[24] P.-C. Hsu and R.-S. Chen, "Analyzing the Mechanisms by Which Digital Platforms Influence Family-School Partnerships among Parents of Young Children," *Sustainability*, vol. 15, no. 24, 16708, Dec. 2023. doi: 10.3390/su152416708

[25] R. Lin, J. Yang, F. Jiang, and J. Li, "Does teacher's data literacy and digital teaching competence influence empowering students in the classroom? Evidence from China," *Educ. Inf. Technol. (Dordr).*, vol. 28, no. 3, pp. 2845–2867, Mar. 2023. doi: 10.1007/s10639-022-11274-3

[26] M. Claro, C. Castro-Grau, J. M. Ochoa, J. E. Hinostroza, and P. Cabello, "Systematic review of quantitative research on digital competences of in-service school teachers," *Comput. Educ.*, vol. 215, 105030, Jul. 2024. doi: 10.1016/j.compedu.2024.105030

[27] L. A. T. Nguyen and A. Habók, "Tools for assessing teacher digital literacy: A review," *Journal of Computers in Education*, vol. 11, no. 1, pp. 305–346, Mar. 2024. doi: 10.1007/s40692-022-00257-5

[28] L. H. Sillat, K. Tammets, and M. Laanpere, "Digital competence assessment methods in higher education: A systematic literature review," *Educ. Sci. (Basel).*, vol. 11, no. 8, 402, Aug. 2021. doi: 10.3390/educsci11080402

[29] J. F. Hair, G. T. M. Hult, C. M. Ringle, and M. Sarstedt, *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*, 3rd ed. Sage Publications, 2021.

[30] J. Henseler, C. M. Ringle, and M. Sarstedt, "A new criterion for assessing discriminant validity in variance-based structural equation modeling," *J. Acad. Mark. Sci.*, vol. 43, no. 1, pp. 115–135, Jan. 2015. doi: 10.1007/s11747-014-0403-8

[31] J. Henseler, *Composite-Based Structural Equation Modeling: Analyzing Latent and Emergent Variables*, The Guilford Press, 2021.

[32] N. Kock, "Common Method Bias in PLS-SEM: A Full Collinearity Assessment Approach," *International Journal of e-Collaboration*, vol. 11, no. 4, pp. 1–10, Oct. 2015. doi: 10.4018/ijec.2015100101

[33] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates, 1988.

[34] M. Li, C. Vale, H. Tan, and J. Blannin, "Factors influencing the use of digital technologies in primary mathematics teaching: Voices from Chinese educators," *Educ. Inf. Technol. (Dordr).*, vol. 30, no. 9, pp. 12573–12608, Jun. 2025. doi: 10.1007/s10639-024-13309-3

[35] M. C. Buchan, J. Bhawra, and T. R. Katapally, "Navigating the digital world: development of an evidence-based digital literacy program and assessment tool for youth," *Smart Learning Environments*, vol. 11, no. 1, 8, Feb. 2024. doi: 10.1186/s40561-024-00293-x

[36] K. A. Soomro, M. Ansari, I. A. Bughio, and N. A. Nasrullah, "Examining gender and urban-rural divide in digital competence among university students," *International Journal of Learning Technology*, vol. 19, no. 3, pp. 380–393, 2024. doi: 10.1504/ijlt.2024.142512

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