Journal of Advanced Sciences and Mathematics Education
Volume 6, Issue 3, 464-486.
e_ISSN: 2798-1606
DOI: 10.58524/jasme.v6i3.1498

Deep learning readiness, self-regulated learning, and numeracy literacy in mathematics education: A PLS-SEM mediation study

Sherly Mayfana Panglinur Yekti*
Universitas PGRI MPU Sindok, INDONESIA

Agustin Patmaningrum
Universitas PGRI MPU Sindok, INDONESIA

Eny Dwi Utami
Universitas PGRI MPU Sindok, INDONESIA

Nayla Sasti Ifadza
Universitas Negeri Surabaya, INDONESIA

Aditya Ramadhan
Universitas PGRI MPU Sindok, INDONESIA

Article Info

Article history:

Received: May 20, 2026
Revised: June 30, 2026
Accepted: Augst 14, 2026

Keywords:

Deep Learning Readiness; Mathematics Education; Numeracy Literacy; PLS-SEM; Self-Regulated Learning.

Abstract

Background: Improving numeracy literacy requires mathematics learning environments that support meaningful engagement while enabling students to regulate their learning processes. However, the mechanism linking Deep Learning Readiness (DLR), Self-Regulated Learning (SRL), and Numeracy Literacy (NL) remains insufficiently understood.
Aims: This study investigated the structural relationships among DLR, SRL, and NL and examined the mediating role of SRL in the DLR–NL relationship.
Method: A cross-sectional survey involved 144 Grade VIII students from three junior secondary schools in Nganjuk Regency, East Java, Indonesia. Data were collected using a PISA-aligned Numeracy Literacy Test (α = .905), a 51-item SRL questionnaire (α = .980) based on Zimmerman's three-phase model, and a Deep Learning Readiness Scale. Data were analyzed using PLS-SEM with 5,000 bootstrap resamples.
Results: DLR was positively associated with SRL (β = .512, $p < .001$) and NL (β = .287, $p < .001$), while SRL was positively associated with NL (β = .483, $p < .001$). The model explained 26.2% of SRL variance and 48.7% of NL variance. SRL partially mediated the DLR–NL relationship (β = .247, VAF = 46.3%).
Conclusion: SRL serves as an important mechanism connecting deep learning readiness with numeracy literacy, highlighting the importance of integrating self-regulatory practices into mathematics learning environments.

To cite this article: Yekti, S. M. P., Patmaningrum, A., Utami, E. D., Ifadza, N. S. & Ramadhan, A. (2026). Deep learning readiness, self-regulated learning, and numeracy literacy in mathematics education: A PLS-SEM mediation study. *Journal of Advanced Sciences and Mathematics Education, 6*(3), 463-486.

INTRODUCTION

The capacity of education systems to develop transferable competencies has become increasingly important in preparing students to respond effectively to complex and rapidly changing social and academic demands. Among these competencies, mathematical reasoning, critical thinking, self-directed learning, and adaptive problem solving are essential for enabling students to use knowledge meaningfully beyond routine classroom situations (Elhilal, 2025; Eti et al., 2026). Numeracy literacy represents an important dimension of these competencies because it requires learners to formulate mathematical problems, employ appropriate concepts and procedures, and interpret mathematical results within relevant contexts (Bolstad, 2023; Manfreda Kolar & Hodnik, 2021; Pratiwi et al., 2024). Nevertheless, the development of numeracy literacy remains a substantial challenge in Indonesian mathematics education, as reflected in students' performance on international and national assessments. This condition indicates that mathematical proficiency cannot be adequately developed through procedural exercises and memorization alone. Students require learning experiences that encourage conceptual understanding, strategic reasoning,

***Corresponding author:**
Sherly Mayfana Panglipur Yekti, Universitas PGRI MPU Sindok, Indonesia
sherlymayfana@upms.ac.id

interpretation, and the flexible application of mathematical knowledge across different situations. Such learning experiences are particularly important at the junior secondary level, where students encounter increasingly complex mathematical ideas while simultaneously developing greater independence in learning. Improving numeracy literacy therefore requires instructional practices that connect mathematical concepts with meaningful contexts and encourage students to actively construct, monitor, and evaluate their understanding. Mathematics learning should consequently provide opportunities for sustained inquiry, problem exploration, multiple forms of reasoning, and reflection rather than emphasizing the reproduction of predetermined solution procedures (Ayari et al., 2025; Doz et al., 2025; Fry et al., 2025; Nilimaa, 2023; Ramaila, 2025). These demands highlight the need for a learning orientation capable of integrating meaningful mathematical engagement with the development of students' cognitive and self-regulatory capacities.

Deep learning has emerged as a relevant pedagogical orientation for responding to these educational demands because it emphasizes meaningful engagement, conceptual understanding, sustained inquiry, and the transfer of knowledge to new contexts. Within mathematics education, deep learning encourages students to establish connections between conceptual and procedural knowledge rather than treating mathematical procedures as isolated rules to be memorized (Alam & Mohanty, 2024b). Its implementation can also provide opportunities for students to investigate mathematical relationships, interpret contextual information, construct solutions, and reflect on the meaning of their results. In Indonesia, deep learning has increasingly received policy attention as an educational approach intended to strengthen the quality and meaningfulness of learning (Fitrah et al., 2025). However, effective deep learning cannot be achieved merely through the formal adoption of a pedagogical policy or the introduction of new terminology into curriculum documents (Adamakis & Rachiotis, 2025; Fitrah et al., 2025; Kovač et al., 2025; McPhail, 2021; Webb et al., 2021). Its implementation depends on the extent to which schools and classrooms possess the instructional conditions necessary to translate deep learning principles into meaningful learning experiences. This study conceptualizes these conditions as Deep Learning Readiness (DLR), which encompasses teacher pedagogical competence, technology integration, instructional design quality, and school support. Pedagogical competence and instructional design enable teachers to organize cognitively demanding and coherent learning experiences, while technology integration can facilitate dynamic representations, interactive exploration, and responsive learning opportunities (Afonso et al., 2025; Jun-on & Suwanreang, 2026). School support further provides the institutional conditions necessary to sustain pedagogical innovation and ensure that deep-learning-oriented practices extend beyond isolated classroom initiatives. Accordingly, DLR can be understood as a multidimensional environmental condition that may contribute to meaningful mathematical engagement, strategic reasoning, and the development of students' numeracy literacy.

The contribution of deep-learning-oriented environments to numeracy literacy may also depend on students' capacity to regulate their own learning, making Self-Regulated Learning (SRL) an important component of the proposed relationship. SRL refers to an active and cyclical learning process through which students establish goals, select strategies, monitor their performance, and reflect on the outcomes of their learning activities (Chen, 2022; Faza & Lestari, 2025; Heirweg et al., 2020; Maiti & Priyaadharshini, 2026). These regulatory processes are particularly important in mathematics because contextual and non-routine problems require students to understand task demands, determine appropriate strategies, monitor mathematical procedures, identify errors, and evaluate the reasonableness of their solutions. Students with stronger self-regulatory capacities are therefore more likely to maintain purposeful engagement and adjust their strategies when an initial mathematical approach does not produce an appropriate solution. Recent evidence indicates that SRL is meaningfully associated with students' learning processes and academic outcomes, while appropriately designed learning environments can support the development of regulatory strategies

(Theobald, 2021). SRL has also received increasing attention within mathematics and numeracy research because students' capacity to manage their own learning can shape how effectively they engage with challenging mathematical tasks (Husna et al., 2024). At the same time, emerging studies of deep learning in Indonesian education have primarily examined its implementation or learning outcomes without sufficiently explaining the psychological processes that may connect learning-environment readiness with numeracy achievement (Latif et al., 2025). Deep Learning Readiness may consequently be associated with numeracy literacy not only through meaningful mathematical learning conditions but also through students' engagement in self-regulatory processes. From this perspective, SRL represents a plausible mechanism through which the characteristics of deep-learning-oriented environments may be connected with students' capacity to formulate, employ, and interpret mathematics in contextual situations. Accordingly, the conceptual framework proposes that DLR is positively associated with SRL (H1), SRL is positively associated with numeracy literacy (H2), DLR is directly associated with numeracy literacy (H3), and SRL mediates the relationship between DLR and numeracy literacy (H4), as illustrated in Figure 1.

Conceptual Framework: Deep Learning Readiness, Self-Regulated Learning, Numeracy Literacy

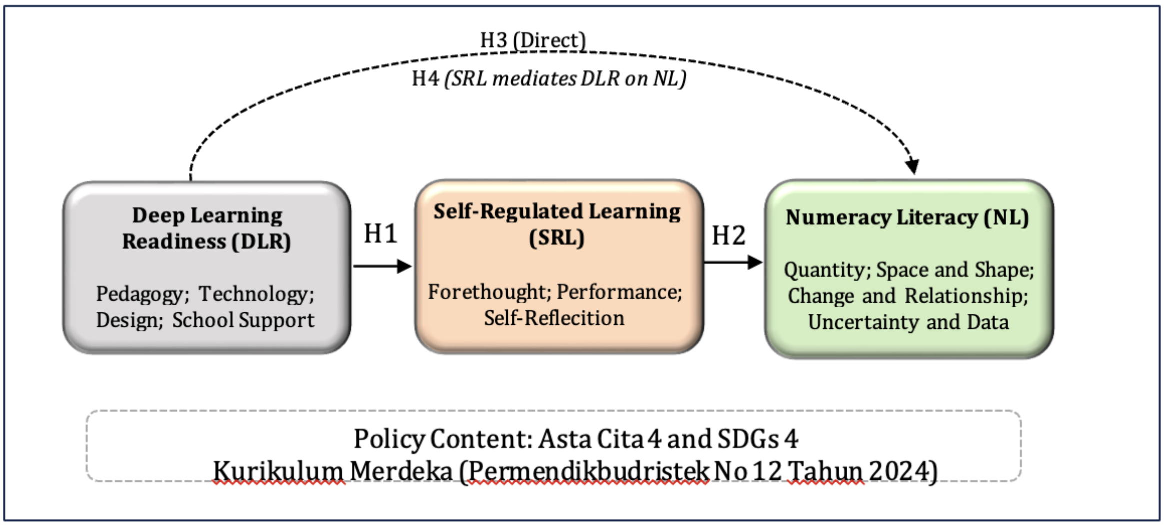

Figure 1. Conceptual Framework with Hypothesized paths (H1-H4)

Although numeracy and mathematical literacy have received substantial attention in educational research, previous studies have predominantly focused on conceptual perspectives of numeracy and mathematical literacy, students' contextual problem-solving processes, proficiency development, and instructional approaches designed to strengthen mathematical literacy (Bolstad, 2023; Grotlüschen et al., 2020; Manfreda Kolar & Hodnik, 2021; Muhaimin et al., 2024). In parallel, Self-Regulated Learning (SRL) research has demonstrated the importance of students' capacity to plan, monitor, evaluate, and adapt their learning across conventional, digital, and technology-supported environments, with evidence indicating its relevance to learning engagement and academic performance (Gambo & Shakir, 2021; Raković et al., 2022; Theobald, 2021; Vosniadou, 2020). Recent research has also begun to examine readiness for implementing deep learning by emphasizing pedagogical, technological, and institutional conditions; however, this line of inquiry has largely developed separately from studies of students' self-regulation and numeracy outcomes (Pahrudin et al., 2025). Consequently, although previous studies provide substantial evidence concerning mathematical literacy, SRL, and deep learning readiness individually, limited empirical evidence explains how these constructs operate simultaneously within mathematics education, particularly whether SRL functions as a mechanism connecting Deep Learning Readiness (DLR) with Numeracy Literacy (NL). Moreover, while mediation analysis and PLS-SEM have been established as useful approaches for examining indirect relationships among theoretically related constructs (Igartua & Hayes, 2021; Rijnhart et al., 2021; Sarstedt et al., 2020), their application to an integrated DLR–SRL–NL model remains underexplored. Therefore, this study addresses this empirical, theoretical, and methodological gap by examining the structural relationships among DLR, SRL, and NL and testing the mediating role of SRL through PLS-SEM, thereby providing a more integrated explanation of how readiness for deep-learning-oriented mathematics environments is associated with students' numeracy literacy through their self-regulatory learning processes.

Based on these research gaps, this study aims to examine the structural relationships among Deep Learning Readiness (DLR), Self-Regulated Learning (SRL), and Numeracy Literacy (NL) among Grade VIII students in Indonesian junior secondary mathematics education. First, the study investigates the relationship between DLR and SRL to determine whether readiness for deep-learning-oriented environments is associated with students' capacity to regulate their learning. Second, it examines the relationship between SRL and NL to determine whether stronger self-regulatory capacities are associated with higher levels of numeracy literacy. Third, the study evaluates the direct relationship between DLR and NL to determine whether readiness for deep learning is independently associated with students' numeracy outcomes. Beyond these direct relationships, the study specifically examines whether SRL mediates the relationship between DLR and NL. This mediation pathway is proposed to provide a more comprehensive explanation of how pedagogical, technological, instructional, and institutional readiness may be connected with numeracy literacy through students' regulatory learning processes. Partial Least Squares Structural Equation Modeling (PLS-SEM) is employed to evaluate the measurement properties of the constructs and simultaneously estimate the hypothesized direct and indirect structural relationships. Through this integrated model, the study seeks to extend previous research that has largely examined deep learning readiness, self-regulated learning, and numeracy literacy separately. The findings are expected to contribute to mathematics education by clarifying the role of students' self-regulatory processes in the relationship between deep learning readiness and numeracy literacy. Ultimately, the study provides an empirical basis for designing mathematics learning environments that simultaneously strengthen readiness for meaningful learning, foster students' self-regulation, and support the development of numeracy literacy.

LITERATURE REVIEW

Deep Learning Readiness (DLR) represents the extent to which educational environments possess the conditions required to implement learning that promotes meaningful understanding, sustained inquiry, and knowledge transfer. Rather than being limited to the adoption of particular teaching strategies, readiness for deep learning involves interconnected pedagogical, technological, instructional, and institutional dimensions. Teacher pedagogical competence constitutes a central dimension because meaningful mathematics learning requires teachers to design cognitively demanding tasks, facilitate conceptual exploration, and connect mathematical ideas with authentic situations (König et al., 2022). Technology integration complements pedagogical competence by providing opportunities for dynamic mathematical representation, interactive exploration, formative assessment, and differentiated learning experiences. The instructional design dimension concerns the alignment of learning objectives, mathematical tasks, learning activities, and assessment practices to ensure that students engage with mathematics beyond procedural reproduction (Adeleke et al., 2025; Canogullari & Radmehr, 2026; Mu et al., 2022; Prediger et al., 2022). School support further provides the infrastructure, leadership, resources, and collaborative professional culture necessary for deep-learning-oriented practices to be implemented consistently rather than as isolated instructional innovations. These dimensions indicate that DLR should be understood as a multidimensional educational condition rather than a single characteristic of teachers or students. In mathematics education, stronger readiness may provide students with greater opportunities to reason, investigate mathematical relationships, use multiple representations, and connect mathematical concepts with contextual problems (Manfreda Kolar & Hodnik, 2021; Sari & Darhim, 2020; Sevinc & Lesh, 2022). Such environments may also encourage students to take greater responsibility for managing their learning because meaningful mathematical tasks frequently require sustained engagement, strategic decision-making, and reflection. DLR therefore provides an environmental foundation from which both students' regulatory capacities and their numeracy literacy may be supported.

Self-Regulated Learning (SRL) provides a complementary learner-centered perspective by explaining how students actively manage cognitive, motivational, and behavioral processes during learning. SRL is commonly conceptualized as a cyclical process consisting of forethought, performance, and self-reflection, through which learners establish goals, implement strategies, monitor progress, and evaluate learning outcomes (Alam & Mohanty, 2024a; Cleary et al., 2023; Khoiriyah & Roberts, 2025; Maiti & Priyaadharshini, 2026; Wu, 2024). During the forethought phase, students analyze learning tasks, formulate goals, select strategies, and establish motivational orientations that guide subsequent actions. The performance phase involves implementing selected strategies, maintaining attentional control, observing progress, and making adjustments when difficulties arise. Self-reflection subsequently enables students to evaluate their performance, identify the effectiveness of strategies, and use these judgments to inform subsequent learning cycles. These processes have particular relevance to mathematics because complex problem solving requires students to coordinate conceptual knowledge, procedural strategies, metacognitive monitoring, and persistence across multiple stages of a task (Theobald, 2021). Evidence from educational research further indicates that SRL can be strengthened when instructional environments explicitly provide strategic guidance, opportunities for reflection, meaningful feedback, and learner autonomy. Within mathematics learning, stronger SRL can enable students to recognize when a strategy is ineffective, reconsider assumptions, verify mathematical procedures, and modify their approaches according to task demands. SRL should therefore not be considered independently from the learning environment because students' regulatory activities can be activated or constrained by the nature of instructional experiences provided to them. This relationship provides a theoretical basis for proposing that greater Deep Learning Readiness is positively associated with students' Self-Regulated Learning.

Numeracy literacy constitutes the principal learning outcome examined in this study and reflects students' capacity to use mathematics meaningfully across contextual situations. Within the PISA framework, mathematical literacy requires students to formulate situations mathematically, employ mathematical concepts and procedures, and interpret or evaluate mathematical outcomes in relation to real-world contexts. Its content structure encompasses quantity, space and shape, change and relationships, and uncertainty and data, representing a broad range of mathematical knowledge required for contemporary problem solving (Ozkale & Ozdemir Erdogan, 2022; Reinhold et al., 2020; Srikoon et al., 2024). Numeracy literacy therefore differs from narrow computational proficiency because successful performance requires students to determine what mathematical information is relevant, construct appropriate representations, select strategies, and evaluate whether resulting solutions are reasonable. Contextual mathematical tasks also demand flexibility because information may be presented verbally, numerically, graphically, symbolically, or through combinations of multiple representations (Hickendorff et al., 2022; Rosita et al., 2026; Torres-Peña et al., 2025; Wahab, 2026). Contemporary studies of mathematical literacy have emphasized contextual problem solving and students' ability to coordinate mathematical knowledge with meaningful situations. Indonesian students continue to demonstrate difficulties with contextual problem solving, multiple representations, and the interpretation of mathematical information, indicating that instructional practices remain important for developing literacy-oriented mathematical competence (Latif et al., 2025). At the same time, mathematical literacy depends on learner characteristics because students must independently regulate strategies and monitor reasoning while solving unfamiliar problems. Research connecting SRL with mathematical literacy suggests that students' regulatory capacity can differentiate how effectively they engage with literacy-oriented mathematical tasks and learning environments. Consequently, numeracy literacy can be understood as an outcome emerging from the interaction between the quality of mathematical learning environments and students' capacity to strategically regulate their engagement with mathematical problems.

The theoretical relationships among DLR, SRL, and numeracy literacy suggest that environmental and individual learning processes should be considered simultaneously rather than as independent determinants of mathematics outcomes. Deep-learning-oriented environments provide cognitive demand, authentic mathematical contexts, strategic guidance, technology-supported exploration, and opportunities for reflection that can encourage students to assume a more active role in learning (Fitrah et al., 2025; Talib et al., 2026). These characteristics correspond closely with the processes required for SRL because goal setting, strategy selection, monitoring, and reflection become meaningful when students engage with challenging and purposeful mathematical activities. Accordingly, DLR is expected to be positively associated with SRL because supportive learning conditions can provide repeated opportunities for students to practice and refine self-regulatory behaviors. SRL is subsequently expected to be positively associated with numeracy literacy because contextual mathematical problem solving requires students to plan approaches, monitor reasoning, evaluate results, and modify strategies when necessary. Empirical research has demonstrated meaningful relationships between SRL and mathematics outcomes, while studies combining SRL with mathematical literacy indicate that regulatory capacity is relevant to students' performance on literacy-oriented tasks (Husna et al., 2024; Theobald, 2021). Recent structural-modeling research in mathematics education similarly demonstrates that SRL can operate alongside other cognitive and motivational constructs in explaining variation in mathematics achievement. The relationship between DLR and numeracy literacy may also occur independently of SRL because cognitively demanding tasks, meaningful contexts, appropriate technological resources, and coherent instructional design can directly expand opportunities for mathematical reasoning. These theoretical arguments support three structural propositions: DLR is positively associated with SRL (H1), SRL is positively associated with numeracy literacy (H2), and DLR is positively associated with numeracy literacy (H3). Together, these relationships establish the theoretical conditions required to examine whether SRL provides an indirect pathway connecting DLR with numeracy literacy.

The mediating role of SRL provides a mechanism-oriented explanation for understanding how readiness for deep-learning-oriented environments may be associated with students' numeracy literacy. Mediation assumes that the relationship between an antecedent and an outcome may operate partly through an intervening construct that represents an explanatory process connecting the two variables (Sarstedt et al., 2020). Within the proposed framework, DLR represents an environmental antecedent, SRL represents the learner-level regulatory mechanism, and numeracy literacy represents the mathematics learning outcome. This configuration recognizes that supportive learning conditions may not automatically translate into stronger numeracy performance unless students actively engage with the opportunities those environments provide. A deep-learning-ready environment can encourage planning through purposeful tasks, monitoring through formative feedback, and reflection through opportunities to evaluate mathematical reasoning, thereby activating processes central to SRL. Stronger SRL may subsequently enable students to engage more effectively with contextual numeracy tasks by sustaining attention, coordinating strategies, identifying errors, and evaluating the appropriateness of mathematical solutions (Ferreira et al., 2022; Granello et al., 2026; Monteiro & Passarinho, 2026). Evidence from contemporary mathematics education suggests that mediation models can provide insights into mechanisms that may remain obscured when instructional conditions and learning outcomes are examined only through direct relationships. PLS-SEM is particularly suitable for examining such models because it permits the simultaneous evaluation of measurement properties and estimation of direct and indirect structural relationships among latent constructs (Sarstedt et al., 2022). The proposed mediation model therefore extends the analysis beyond whether DLR and SRL are individually related to numeracy literacy toward explaining how these constructs may operate together within a coherent structural process. Accordingly, the fourth hypothesis proposes that Self-Regulated Learning mediates the relationship between Deep Learning Readiness and Numeracy Literacy (H4).

METHOD

Research Design

This study employed a quantitative cross-sectional correlational design to examine the structural relationships among Deep Learning Readiness (DLR), Self-Regulated Learning (SRL), and Numeracy Literacy (NL) in junior secondary mathematics education. Partial Least Squares Structural Equation Modeling (PLS-SEM) was employed as the primary analytical approach because the study focused on prediction-oriented modeling and the examination of theoretically specified relationships among latent constructs. PLS-SEM was considered appropriate for three main reasons. First, the study sought to extend the theoretical understanding of the relationships among DLR, SRL, and NL rather than confirm an established covariance structure, making a variance-based approach suitable for the analytical purpose. Second, the conceptual model incorporated multidimensional higher-order constructs represented through lower-order dimensions, requiring an analytical approach capable of accommodating hierarchical measurement structures. Third, the sample size of 144 students was considered adequate for estimating the proposed structural model and exceeded the recommended minimum requirements for PLS-SEM based on established sample-size estimation procedures. Within the structural model, DLR was specified as the exogenous construct, SRL as the mediating construct, and NL as the endogenous outcome. The model examined the direct relationships between DLR and SRL, SRL and NL, and DLR and NL, together with the indirect DLR → SRL → NL pathway. Because all substantive variables were observed within a cross-sectional design, the estimated structural paths were interpreted as predictive associations rather than definitive evidence of causal effects. This design therefore enabled the simultaneous evaluation of the measurement properties of the constructs and the structural relationships proposed in the conceptual framework.

Participant

The participants were 144 Grade VIII students drawn from five classes across three junior secondary schools in Nganjuk Regency, East Java, Indonesia. The participating institutions were SMP Negeri 1 Rejoso (n = 68), SMP Muhammadiyah 1 Nganjuk (n = 43), and MTs Al Huda Bogo (n = 33). The schools were purposively selected to provide institutional diversity within the research setting and to capture variation in students' mathematics learning environments. All participating schools had implemented the Kurikulum Merdeka and had been introduced to the Deep Learning initiative through dissemination activities conducted by the East Java BBGTK or the Nganjuk District Education Office between June and August 2025. The student sample consisted of 76 females (52.8%) and 68 males (47.2%), providing a relatively balanced gender distribution. Participants ranged from 13 to 15 years of age, with a mean age of 13.6 years (SD = 0.71). Grade VIII students were selected because they had sufficient experience with the participating schools' mathematics learning environments while also engaging with mathematical content requiring increasingly complex reasoning and contextual problem solving. The sample size was considered sufficient for estimating the proposed PLS-SEM model based on the structural complexity and established minimum sample-size considerations for variance-based structural equation modeling. Pooling students from the three schools was further examined through the Measurement Invariance of Composite Models (MICOM) procedure to establish whether the constructs were measured comparably across institutional groups. Configural invariance, compositional invariance, and equality of composite means and variances were assessed before the complete sample was used for the primary structural analysis.

Instrument and Data Collection

Three instruments were employed to measure NL, SRL, and DLR. Numeracy Literacy was assessed using a PISA-aligned Numeracy Literacy Test developed by the research team based on the PISA 2022 mathematics framework and organized around four content domains: quantity, space and shape, change and relationships, and uncertainty and data. The test consisted of open-response items designed to assess students' capacity to engage with contextual mathematical problems, with scoring informed by the six PISA proficiency levels. Four content-domain subscores were subsequently used to represent NL within the measurement model, and the instrument demonstrated high internal consistency with Cronbach's $\alpha = .905$. The Self-Regulated Learning questionnaire initially contained 54 items and was pilot-tested with 34 students outside the main sample, after which three items with low item-total correlations were removed, resulting in a final 51-item instrument. The retained items were rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree) and represented the three dimensions of forethought, performance control, and self-reflection, which were operationalized as lower-order dimensions of the higher-order SRL construct using a two-stage approach. The SRL instrument demonstrated excellent internal consistency, with Cronbach's $\alpha = .980$. DLR was measured using a 20-item scale developed from the deep learning framework and adapted to the Indonesian school context, comprising teacher pedagogical competence (5 items, $\alpha = .87$), technology integration (5 items, $\alpha = .83$), instructional design quality (5 items, $\alpha = .86$), and school support (5 items, $\alpha = .85$). Three mathematics education specialists evaluated the content validity of the DLR scale, producing an average Content Validity Index of .91. Students rated their perceived experiences of these conditions during recent mathematics lessons.

Data were collected between June and September 2025 under standardized school-based administration procedures. Each instrument was administered on a separate, non-consecutive day to minimize response fatigue and potential carryover effects between measurements. The Numeracy Literacy Test was administered first in proctored classroom settings during regular mathematics lessons, with students allocated 90 minutes to complete the assessment. The SRL questionnaire was administered during a second session, followed by the DLR scale on a third separate day. In addition to the primary quantitative measures, contextual information was obtained through nine classroom observations, focus group discussions involving teachers and school principals, and document analysis of curriculum plans, lesson plans, and assessment records. These supplementary sources were used for contextual triangulation and to provide a broader understanding of the participating schools' learning environments. However, the contextual data were not incorporated as variables in the PLS-SEM analysis because the structural model was specifically designed to examine the quantitative relationships among DLR, SRL, and NL. This separation ensured that the statistical model remained consistent with the operational definitions and measurement structure established for the three focal constructs.

Data Analysis

Data analysis was conducted using SmartPLS 4.0 through four sequential analytical stages comprising measurement model assessment, structural model evaluation, mediation analysis, and Importance–Performance Map Analysis (IPMA). In the first stage, the measurement model was evaluated using indicator loadings, internal consistency reliability, convergent validity, and discriminant validity. Indicators with outer loadings below .708 were considered for removal, composite reliability values of at least .70 were used to establish internal consistency, and Average Variance Extracted (AVE) values of at least .50 were required to establish convergent validity. Discriminant validity was examined using the Heterotrait-Monotrait ratio (HTMT), while the multidimensional higher-order constructs were estimated according to their specified hierarchical measurement structures. In the second stage, the structural model was assessed for collinearity using Variance Inflation Factor (VIF) values, followed by estimation of path coefficients, coefficient of determination (R^2), effect sizes (f^2), and predictive relevance (Q^2). The statistical significance of the structural paths was examined using two-tailed bootstrapping with 5,000 resamples and bias-corrected confidence intervals. Predictive performance was additionally examined using PLSpredict, while the Standardized Root Mean Square Residual (SRMR) and Normed Fit Index (NFI) were reported as supplementary indicators of overall model fit. In the third stage, mediation analysis examined the indirect DLR → SRL → NL pathway and the corresponding bootstrap confidence interval, while Variance Accounted For (VAF) was used as supplementary information to characterize the relative contribution of the indirect pathway. In the fourth stage, IPMA was performed by combining the total effects of the predictor constructs on NL with their performance scores transformed to a 0–100 scale, thereby identifying constructs and indicators with relatively high importance but lower performance. Common method bias was additionally examined through Harman's single-factor test and a full-collinearity assessment, with the largest unrotated factor accounting for 28.7% of the variance and inner VIF values ranging from 1.21 to 2.43. Finally, the MICOM procedure was used to evaluate measurement invariance across the three participating schools before pooled structural analysis was conducted.

Research Procedure

The research was implemented through a systematic sequence beginning with conceptual model development and concluding with mediation and importance–performance analyses. First, the theoretical relationships among DLR, SRL, and NL were established and translated into the hypothesized structural model, with DLR specified as an environmental antecedent, SRL as the proposed mediator, and NL as the learning outcome. Second, the three measurement instruments were developed or adapted according to their respective conceptual frameworks and subsequently subjected to expert validation and preliminary testing. The SRL instrument was pilot-tested with 34 students, resulting in the removal of three items with inadequate item-total correlations, while the DLR instrument underwent content validation by three mathematics education specialists. Third, the participating schools were purposively selected, and students from five Grade VIII classes were recruited for the main study. Fourth, quantitative data were collected between June and September 2025 through three separate administration sessions, beginning with the Numeracy Literacy Test and followed by the SRL questionnaire and DLR scale. Contextual triangulation was conducted alongside quantitative data collection through classroom observations, focus group discussions, and analysis of relevant instructional documents, although these data were not included in the structural model. Fifth, the quantitative dataset was screened and prepared for PLS-SEM analysis, followed by evaluation of measurement invariance across the participating schools. Sixth, the measurement model was assessed to establish indicator reliability, internal consistency, convergent validity, and discriminant validity before interpretation of structural relationships. Seventh, the structural model was evaluated to determine the magnitude, significance, explanatory power, and predictive relevance of the hypothesized DLR → SRL, SRL → NL, and DLR → NL relationships. Finally, mediation analysis was conducted to examine the indirect DLR → SRL → NL pathway, followed by IPMA to identify the dimensions that may warrant priority in efforts to strengthen students' numeracy literacy.

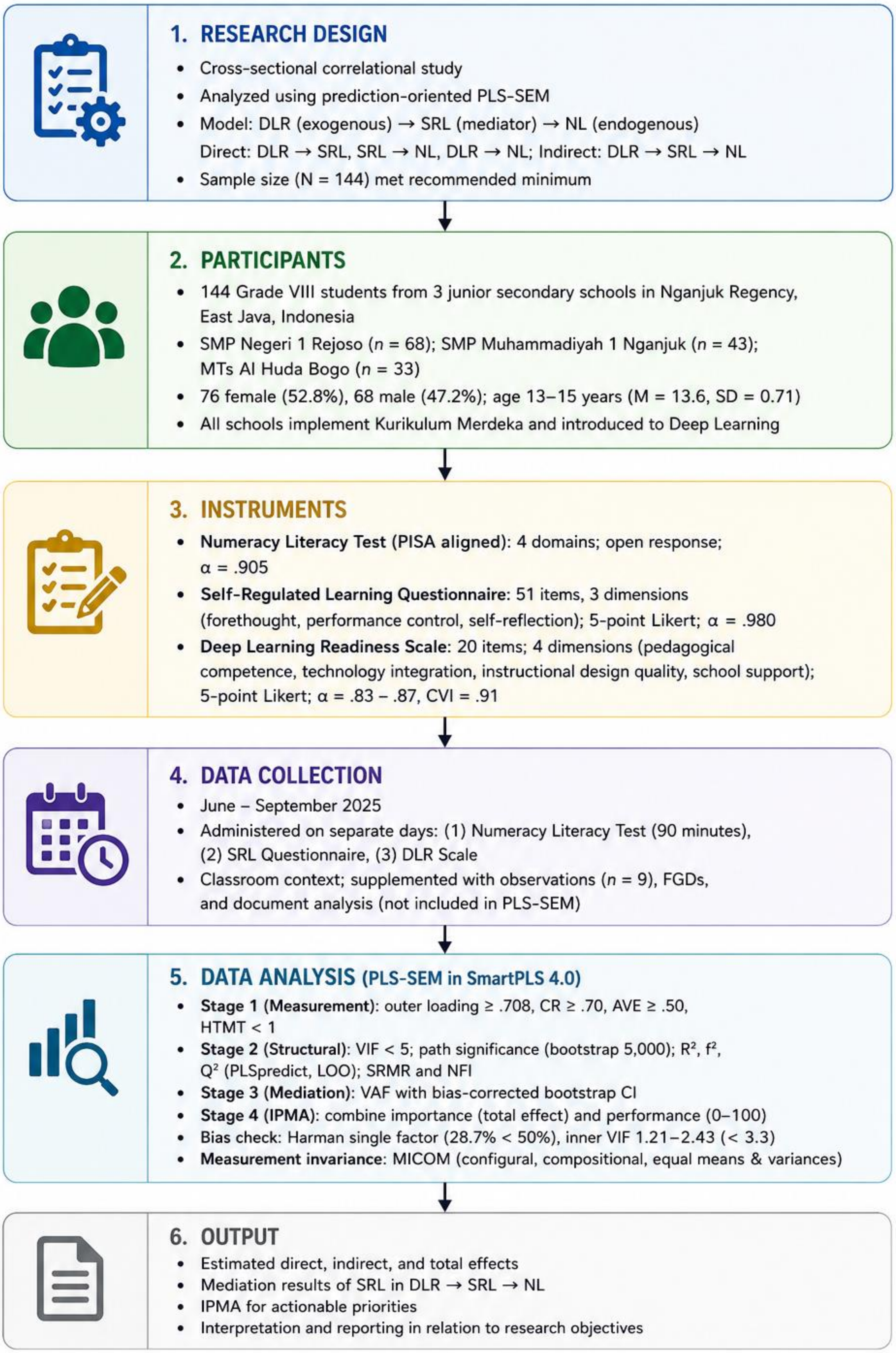

Figure 1. Research Method Flow

RESULTS AND DISCUSSION

Results

Data for the latent construct composite scores were moderately high for DLR (M = 3.42, SD = 0.68; theoretical range, 1 – 5) and SRL (M = 3.55 , SD = 0.71), and low to moderate with respect to NL (M = 55.3, SD = 18.4 ; theoretical range of NC sub scores none to maximum possibility given respondents number). All indicators showed skewness and kurtosis value within the limits of acceptance of ±1.0, which was consistent with the assumption of approximate normality. All pearson zero order correlations among three composites scores were positive and significant (r = 0.42 to 0.59, p <. 001), offering initial evidence in favor of the proposed relationships.

Table 1. Descriptive Statistics and Zero Order Correlations among Study Variables

Variable	M	SD	Skew.	Kurt.	1	2	3
1. Deep Learning Readiness (DLR)	3.42	0.68	-0.31	-0.18	(.82)		
2. Self-Regulated Learning (SRL)	3.55	0.71	-0.24	-0.42	.52**	(.85)	
3. Numeracy Literacy (NL)	55.3	18.4	0.18	-0.66	.42**	0.59**	(.83)

Note N=144. **p< .001 Cronbach's alpha values shown on the diagonal in parentheses.

All outer loadings were higher than. 708 threshold (range 0.756 – 0.892 ; see Table 2). These constructs exhibited high internal consistency reliability (all composite reliability ρc > 0.70) 0,876 to 0,911 and Cronbach a from 0.821 to 0.853. Convergent validity was established: AVE values were greater than threshold of 50 across all constructs (range 0.640 – 0.767).

Table 2. Measurement Model: Indicator Loadings, Reliability, and Convergent Validity

Construct	Indicator	Loading	α	ρc	AVE
Deep Learning Readiness	DLR1 – Pedagogical Competence	0.812	0.821	0.876	0.640
	DLR2 – Technology Integration	0.756			
	DLR3 – Instructional Design	0.847			
	DLR4 – School Support	0.788			
Self-Regulated Learning	SRL_FT – Forethought	0.871	0.853	0.911	0.767
	SRL_PVC – Performance	0.892			
	SRL_SR – Self-Reflection	0.864			
Numeracy Literacy	NL1 – Quantity	0.823	0.829	0.888	0.656
	NL2 – Space and Shape	0.764			
	NL3 – Change and Relationship	0.851			
	NL4 – Uncertainty and Data	0.798			

Note.$\alpha = Cronbach'sAlpha$; $\rho c = composite\ reliability$; $AVE = Average\ Variance\ Extracted.\ All\ loadings\ significant.$

Heterotrait Monotrait Ratio (HTMT) of correlations, the most robust criterion at present, was used to assess discriminant validity. No HTMT values exceeded the conservative 0.85 cut off for confirming the three constructs as being empirically distinct (see Table 3). The Fornell Larcker criterion was also met (i.e., for the guidelines, the square root of the average variance extracted (AVE) for each construct is more than that of its correlations with any other constructs).

Table 3. Discriminant Validity: Heterotrait Monotrait Ratio (HTMT) Matrix

	DLR	SRL	NL
Deep Learning Readiness (DLR)	-		
Self-Regulated Learning (SRL)	0.612	-	
Numeracy Literacy (NL)	0.554	0.681	-

Note. All HTMT values below the conservative threshold of 0.85, confirming discriminant validity

Before assessing path coefficients, collinearity diagnostics were checked. No problematic collinearity exist since all inner model VIF values were below 2.5 (range 1.21 – 2.43). Standardized path coefficients were estimated with a bootstrap analysis (n = 5000, bias corrected and accelerated 95% CIs). All three direct paths was positive and statistically significant, in fact Table 4.

Table 4. Structural Model: Path Coefficients, t – statistics, and Effect Sizes

Hypothesis	Path	β	SE	t	p	95% CI	$f2$	Decision
H1	$DLR \rightarrow SLR$	0.512	0.065	7.876	<.001	[.387, .638]	0.357	Supported
H2	$SLR \rightarrow NL$	0.483	0.070	6.904	<.001	[.346, .615]	0.291	Supported
H3	$DLR \rightarrow NL$	0.287	0.075	3.825	<.001	[.142, .431]	0.118	Supported

Note. N = 144 Bootstrap resamples = 5000 (BCa intervals). f2: 0.02 = small, 0.15 = medium, 0.35 = large)

The effect sizes ($f2$) indicated that total effect of DLR on SRL was large ($f2$ = 0.357), that of SRL to NL was moderate to large $f2$ = 0.291), and that of DLR directly on NL was small to medium ($f2$ = 0.118). Combined predictors explained a significant amount of variance in students' numeracy literacy $R2 = 0.262$ $for\ SRL$ ($adjusted\ R2$ = 0.257) and $R2 = 0.487$ $for\ NL$ ($adjusted\ R2$ = 0.479). The PLSpredict $Q2$ values were positive for the two endogenous constructs: $Q2$ = 0.193; $Q2$ = 0.301), confirming out of sample predictive relevance. The root mean square residual was SRMR = 0.058 (below the recommended 0.08 threshold), and the normed fit index was NFI = 0.91, all providing adequate support for approximate model fit.

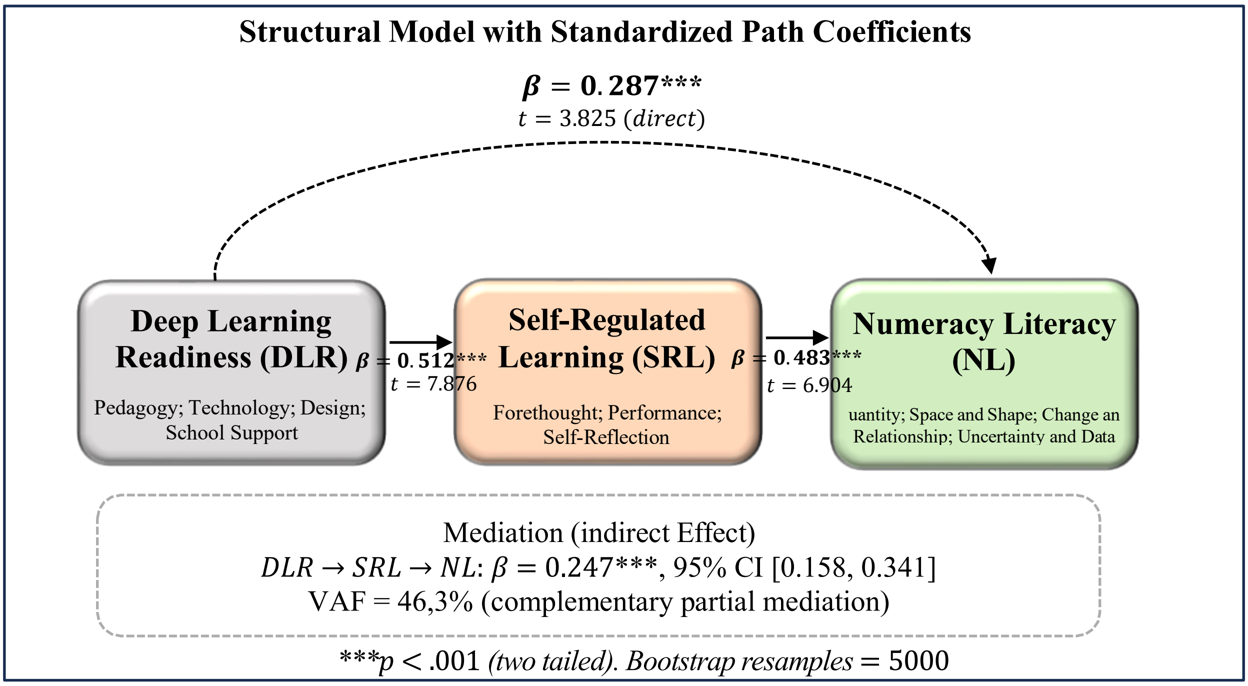

Figure 2. Structural Model with Standardized Path Coefficients, t-statistics, and R^2 values

Using the variance accounted for (VAF) method proposed within PLS-SEM, SRL was tested as mediator between DLR and NL (Nitzl et al., 2016). The mediating effect of SRL on the relationship between DLR and NL was statistically significant: β = 0.247, SE = 0.046, t = 5.426, p < .001, 95% bias corrected and accelerated CI [0.158, 0.341]. The partial mediation was confirmed by the fact that DLR had a significant direct effect on NL, even after considering mediator. VAF was $\frac{0.247}{0.247+0.287} = 0.463$ or 46.3% in the range of (20% – 80%), which indicates partial mediation. Since both direct and indirect effects are positive and statistically significant, this pattern indicates complementary partial mediation, indicating medium sized SRL functions as one of many conduits between DLR and NL.

Table 5. Mediation Analysis: Direct, Indirect, and Total Effects of DLR on NL

Effect Type	Path	β	t	p	95% CI	Mediation
Total Effect	$DLR \rightarrow NL$	0.534	8.215	< .001	[0.402, 0.660]	-
Direct Effect	$DLR \rightarrow NL$	0.287	3.825	< .001	[0.142, 0.431]	-
Indirect Effect	$DLR \rightarrow SRL \rightarrow NL$	0.247	5.426	< .001	[0.158, 0.341]	Partial (VAF = 46.3)

Note. VAF = variance accounted for (indirect/ total effect). Bootstrap resamples $= 5000$.

To convert the structural estimates into actionable priorities, an Importance Performance Matrix Analysis (IPMA) was performed focusing on Numeracy Literacy as target construct (Table 6). Importantly, importance values are a standardized sum of the total effect (i.e., direct plus indirect) exerted by each predictor on NL across all pathways through SRL and performance values indicate where means for constructs were converted to a 1 – 100 scale. The analysis shows that DLR has the highest important collectively (0.534) with the lowest performance (60.5). SRL integrates high importance (0.483) with moderate performance (63.7). Following the IPMA priority logic, constructs in the high importance or low performance quadrant are those that should be targeted for the most urgent intervention, indicating that optimizing students learning conditions above all within dimensions of pedagogical and instructional design related to deep learning readiness will achieve greater marginal gains compared to other improvement areas.

Table 6. Importance Performance Map Analysis (IPMA) for Numeracy Literacy

Construct	Importance (Total effect)	Performance (0 – 100)	Priority Quadrant
Deep Learning Readiness (DLR)	0.534	60.5	High importance/ low performance
Self-Regulated Learning (SRL)	0.483	63.7	High Importance/ Moderate Performance

Note. Importance = total standardized effect on NL from the structural model. Performance = rescaled mean construct score (0-100)

All four hypotheses were supported. Deep Learning Readiness had a large positive influence on Self-Regulated Learning ($H1$: β = 0.512, p < .001) and estimated e very modest direct positive effect on the average Literacy Numeracy ($H3$: β = 0.287, p < .001). Self-Regulated Learning had a medium to large positive effect on Numeracy Literacy ($H2$: β = 0.483, p < .001). The mediation pathway $DLR \rightarrow SRL \rightarrow NL$ was significant and together accounts for 46,3% of the total effect, supporting H4 with a complementary partial mediation pattern. The model, together explained 48,7% variance in numeracy literacy and results from IPMA implied that improvement of deep learning readiness is the most important to implement first priority. This study empirically examines the structural and mediation relationships between these two variables: Deep Learning Readiness (DLR), Self-Regulated Learning (SRL), and Numeracy Literacy (NL), which advances existing knowledge on how deep learning environments translate into numeracy outcomes in Indonesian junior secondary mathematics. Four findings warrant detailed discussion.

Deep Learning Readiness as Driver of Self-Regulated Learning

The positive effect of DLR on SRL, the large positive effect of DLR (β = 0.512) support recent theoretical accounts that present deep learning environments as developmentally conducive contexts for the promotion of self regulatory skills. When teachers create tasks in which students are required to engage with inquiry over time, model strategic thinking themselves, integrate authentic and effective uses of technologies into the classroom practices they adopt for learning designs that key support institutional culture, task design draws upon all three core SRL phases (plan, monitor, reflect). This observation corroborates (König et al., 2022) finding that pedagogical environments with strong instructional alignment and cognitive activation consistently predict gains in students' self regulatory dispositions, the reliability of these findings is reinforced by Theobald's (Theobald, 2021) meta analytic evidence that direct SRL instruction is more productive within than supplementary to subject matter teaching. This means that SRL is not an independent attribute to be developed through separate interventions, but rather a learning capability fostered by ongoing engagement with cognitively challenging well crafted instruction.

Self-Regulated Learning as Predictor of Numeracy Literacy

A medium to large effect of SRL on NL was found (β = 0.483) extends previous Indonesian studies (Husna et al., 2024; Yekti et al., 2022) but uses a more stringent SEM framework which accounts for measurement error and the direct effect on readiness for instructional implementation. SRL students bring to bear clearer goal orientations, a broader selection of strategies, more systematic monitoring of errors, and greater persistence on non routine behaviours that are directly relevant to the multi step contextual reasoning called for by PISA aligned numeracy literacy. This finding aligns with meta analytic evidence on the effectiveness of SRL supportive instruction on academic outcomes, where average intervention effect sizes of d = 0.69 have been documented, particularly pronounced in mathematics context, the current path coefficient (β = 0.483, $f2$ = 0.291) aligns with this pattern and likely reflects both the measurement quality of the SRL instrument as well as the substantive cognitive demands inherent in PISA aligned numeracy literacy tasks.

Complementary Partial Mediation: Two Pathways to Numeracy Outcomes

Perhaps most importantly, the finding is a complementary partial mediation. SRL constitutes 46.3% of the total effect of DLR on NL, but a considerable direct effect remains. This trend reflects that deep learning milieu function via two or more pathways: (a) an indirect, self regulatory path that strengthens capacity for mathematical reasoning through repeated interactions with elements of cognitive frameworks engendered by, and growing from, those experiences, and (b) a direct path composed by meaningful engagement with well designed mathematics tasks. The key implication for practice is that optimizing just one pathway will result in only partial benefits. For example, a school could achieve direct cognitive gains through investment in teacher pedagogical training but will not accrue regulatory benefits if the underlying pedagogy does not include embedded SRL scaffolding. Conversely, a school that adds SRL prompts to a procedurally driven curriculum would witness limited benefit because the explicit tasks lack the sustained regulation activation needed to engage regulatory processes. Thus, were consistent with, comprehensive implementation of deep learning must simultaneously attend to both pathways, in line with systemic reform perspectives that warn against piecemeal change, and more recently Indonesian scholarship calling for holistic rather than additive educational transformation (Budirahayu & Saud, 2023; Hunaepi et al., 2024).

Implications for Asta Cita and SDGs 4 Implementation

The result have clear implications for successful efforts to operationalize the national Asta Cita agenda and SDGs 4, within Indonesian mathematics education. Asta Cita 4 focuses on quality education that enhances human capital with the ability to create critical reasoning, creativity, and collaboration as well as self directed learning. Result from the current study highlight that in order to achieve these goals, we need coordinated investment across all four DLR dimensions of pedagogical competence (knowledge), technology integration skills, instructional design and school support focusing specifically on integrating SRL scaffolding into mathematics teaching. For the learning measure (SDG 4.1: minimum proficiency in adolescent literacy and numeracy), a relatively high $R2$ for NL (0.487%) provides evidence that the modeled antecedents are responsible for a major portion of variance in outcomes and thus can be objects of focused policy intervention (i.e., evidence based). In particular, the data support investments in (a) long term sustained job embedded professional learning for teachers about integrating deep learning pedagogy and SRL scaffolding into their practice, (b) digital infrastructure to be able to leverage dynamic mathematics tools like GeoGebra, Desmos, or adaptive platforms more meaningfully than traditional methods can allow tolerable access flags.

Theoretical and Methodological Contributions

In addition to its practical implications, this study contributes to the literature in three ways. Theoretically, its connects deep learning theory, self regulated learning theory, and frameworks of numeracy literacy in a common empiric mediation model. Previous work has evidenced these strands as separate, however the present results show that they are interdependent over time and provides support for sociocultural and ecological theories of learning which we consider learning environments and learner capacities to be mutually constitutive. From a methodological perspective, this research demonstrates how PLS-SEM may be applied in educational contexts where models are complex, the aim is to predict rather than explain relationships between constructs and sample sizes are modest. Under this logic, high measurement model evidence (composite reliabilities > 0.87, AVE > 0.640, $R2NL$ = 0.487), excellent structural model variance explanation 0.487), and substantial partial mediation supply a methodologically robust vehicle for subsequent intervention studies to follow. Apart from a notable gap in the regional literature, this study also provides the first evidence of mediation on the basis of PLS-SEM through numeracy literacy via SRL with regard to deep learning readiness.

Discussion

The findings demonstrate that Deep Learning Readiness (DLR) is positively and substantially associated with students' Self-Regulated Learning (SRL), as indicated by the standardized path coefficient (β = 0.512, $p < .001$) and a large effect size (f^2 = 0.357). This result suggests that mathematics learning environments characterized by pedagogical competence, meaningful technology integration, coherent instructional design, and school support provide conditions that are conducive to students' capacity to regulate their learning. The finding is consistent with who emphasized that instructional environments characterized by strong pedagogical quality and cognitive activation can facilitate students' active engagement with learning processes (König et al., 2022). It also complements meta-analytic evidence showing that SRL-related interventions contribute to improvements in students' learning strategies, motivation, and academic performance (Theobald, 2021). Within a deep-learning-oriented mathematics environment, students are expected not merely to reproduce mathematical procedures but to establish learning goals, explore alternative strategies, monitor their reasoning, and reflect on the effectiveness of their solutions. Such activities correspond closely to the forethought, performance, and self-reflection processes that constitute the central dimensions of SRL. The relatively strong DLR–SRL relationship identified in this study therefore indicates that self-regulation should not be regarded exclusively as an individual characteristic that develops independently of classroom conditions. Instead, students' regulatory capacities appear to be associated with the quality of learning opportunities provided through pedagogical practices and the broader instructional environment. This interpretation extends previous discussions of deep learning by demonstrating empirically that readiness for its implementation is associated not only with instructional quality but also with students' internal regulation of mathematical learning. Accordingly, strengthening DLR may provide an important environmental foundation for cultivating students who can assume greater responsibility for planning, monitoring, and evaluating their mathematical learning.

The results further reveal that SRL is positively associated with Numeracy Literacy (NL), with β = 0.483 ($p < .001$) and $f^2 = 0.291$, indicating a moderate-to-large contribution within the structural model. This finding supports previous Indonesian studies reporting meaningful relationships between students' self-regulatory characteristics and mathematics-related outcomes (Husna et al., 2024; Yekti et al., 2022). It also corresponds with whose meta-analysis demonstrated that strengthening SRL strategies can produce meaningful improvements in academic performance and students' regulation of learning (Theobald, 2021). The present findings extend this evidence specifically to numeracy literacy, an outcome that requires students to formulate contextual situations mathematically, employ relevant mathematical knowledge, and interpret the resulting solutions. PISA-aligned numeracy tasks frequently involve non-routine situations in which students cannot rely exclusively on memorized algorithms and must instead identify relevant information, select appropriate strategies, monitor intermediate results, and evaluate the reasonableness of their conclusions. These cognitive demands are closely aligned with the regulatory behaviors represented by the SRL construct, providing a theoretical explanation for the relatively strong structural relationship observed in this study. Students with stronger forethought may approach numeracy problems with clearer objectives and more deliberate strategies, while effective performance control can support persistence, monitoring, and adjustment during problem solving. Self-reflection may further enable students to detect inconsistencies, reconsider inappropriate procedures, and evaluate whether mathematical results are meaningful within the original context. Thus, the present study advances earlier findings by showing that SRL is associated not merely with general mathematics achievement but with students' ability to use mathematics meaningfully in literacy-oriented contexts. These results reinforce the importance of embedding opportunities for goal setting, strategic monitoring, error analysis, and reflection within mathematics instruction rather than treating SRL as an additional competency separated from mathematical content.

Another important finding concerns the direct and indirect relationships between DLR and numeracy literacy, which provide evidence of complementary partial mediation through SRL. DLR remained directly associated with NL after SRL was included in the model (β = 0.287, $p < .001$), while the indirect DLR → SRL → NL effect was also significant (β = 0.247, $p < .001$, 95% CI [0.158, 0.341]). The total effect of DLR on NL reached β = 0.534, and the VAF value of 46.3% indicates that a substantial proportion of this relationship operates through students' self-regulatory learning processes. Because both the direct and indirect coefficients were positive and statistically significant, the results indicate complementary partial mediation rather than complete mediation. This pattern provides a more differentiated explanation of the DLR–NL relationship by indicating that readiness for deep learning may be connected with numeracy outcomes through at least two complementary pathways. The indirect pathway suggests that supportive deep-learning conditions are associated with stronger numeracy literacy partly because they facilitate students' planning, monitoring, strategic adaptation, and reflection, whereas the remaining direct pathway suggests that meaningful tasks and coherent instructional experiences may also contribute to numeracy outcomes independently of SRL. This interpretation is consistent with contemporary perspectives emphasizing that sustainable educational improvement requires coordinated changes in instructional conditions and learner processes rather than isolated interventions (Budirahayu & Saud, 2023; Hunaepi et al., 2024). Consequently, strengthening teacher pedagogical competence or technological resources without providing opportunities for students to regulate their learning may capture only part of the potential benefit of deep-learning-oriented mathematics instruction. Conversely, introducing isolated SRL strategies into predominantly procedural mathematics classrooms may be insufficient if students are not consistently exposed to meaningful problems that require those regulatory strategies to be activated. The mediation findings therefore constitute a central contribution of this study by demonstrating that DLR and SRL function as complementary components within an integrated pathway associated with students' numeracy literacy.

The explanatory and predictive properties of the model further strengthen the interpretation of these structural relationships and provide practical priorities for mathematics education. DLR explained 26.2% of the variance in SRL (R^2 = 0.262), whereas DLR and SRL jointly explained 48.7% of the variance in numeracy literacy (R^2 = 0.487), indicating that the proposed constructs account for a meaningful proportion of differences in students' numeracy outcomes. Positive Q^2 values for SRL (0.193) and NL (0.301) additionally indicate predictive relevance beyond the estimation sample, while SRMR = 0.058 and NFI = 0.91 provide supplementary evidence that the proposed model represents the observed relationships adequately. More importantly, the IPMA extends these statistical findings by showing that DLR had the highest importance for numeracy literacy (0.534) while demonstrating comparatively lower performance (60.5) than SRL (63.7). This combination places DLR in a high-importance and lower-performance position, suggesting that improvements in deep learning readiness may offer a particularly relevant target for educational development. The finding is compatible with the broader deep learning literature emphasizing that pedagogical transformation depends on coordinated attention to instructional competence, learning design, technological resources, and organizational support rather than reliance on individual teaching techniques. In the Indonesian context, this priority is especially relevant because implementation of deep learning within mathematics classrooms requires teachers to translate broad curricular aspirations into cognitively demanding and contextually meaningful learning activities. Teacher professional development may therefore need to move beyond conceptual introductions to deep learning and provide sustained opportunities to design numeracy tasks, integrate self-regulatory scaffolding, use digital mathematical resources purposefully, and evaluate students' reasoning processes. At the school level, leadership and institutional support are similarly important for providing time, infrastructure, collaborative teacher networks, and professional learning arrangements that enable these practices to become sustained components of mathematics instruction. In this respect, the IPMA results complement the structural model by translating statistical associations into priorities that can inform mathematics instructional development while avoiding the assumption that any single component alone will automatically improve numeracy outcomes.

Taken together, the findings provide theoretical, methodological, and educational contributions by integrating DLR, SRL, and numeracy literacy within a unified mediation model rather than examining these constructs as separate determinants of mathematics learning. Previous studies have generated substantial evidence concerning SRL, mathematical achievement, instructional quality, and deep-learning-oriented practices, yet comparatively limited attention has been directed toward the mechanism through which readiness for deep learning may be associated with numeracy literacy through students' regulatory processes. The present study addresses this issue by demonstrating that DLR has both a direct relationship with numeracy literacy and an indirect relationship operating through SRL, while the model collectively explains 48.7% of the variance in numeracy literacy. Methodologically, the use of PLS-SEM permits simultaneous consideration of measurement quality, direct structural relationships, mediation, predictive relevance, and importance–performance priorities, thereby providing a more integrated analysis than conventional bivariate approaches (Cepeda et al., 2024; Vipakul & Phuthong, 2026; Zayed et al., 2026). The satisfactory measurement properties, including composite reliability values ranging from 0.876 to 0.911, AVE values from 0.640 to 0.767, and HTMT values below 0.85, further indicate that DLR, SRL, and NL were empirically distinguishable constructs within the proposed model. These results provide support for conceptualizing numeracy development as an interaction between environmental opportunities and learner-level regulatory processes rather than as the consequence of either dimension independently. From an educational perspective, this interpretation aligns with current efforts to strengthen meaningful learning and numeracy competence by suggesting that instructional reform should simultaneously address classroom conditions and students' capacity to regulate mathematical learning. The findings are also relevant to the broader objectives of Asta Cita and SDG 4 because improving numeracy proficiency requires educational environments capable of supporting reasoning, independence, meaningful participation, and the application of mathematical knowledge to authentic situations. Nevertheless, because the study employed a cross-sectional correlational design, the structural coefficients and mediation pathway should be interpreted as theoretically informed associations rather than definitive evidence that DLR causally produces changes in SRL or numeracy literacy. Overall, the evidence suggests that strengthening deep learning readiness while deliberately cultivating self-regulated learning represents a promising integrated direction for supporting numeracy literacy in Indonesian junior secondary mathematics education.

Implications

The findings provide practical implications for strengthening numeracy literacy through the integration of Deep Learning Readiness (DLR) and Self-Regulated Learning (SRL). The significant relationships among DLR, SRL, and Numeracy Literacy (NL) indicate that effective mathematics learning requires both supportive instructional environments and students' capacity to regulate their learning. Teachers should therefore design meaningful and contextual mathematical tasks that encourage students to plan strategies, monitor reasoning, and reflect on their solutions. The partial mediation of SRL further indicates that deep learning environments may support numeracy outcomes both directly and through students' self-regulatory processes. Consequently, teacher professional development should integrate deep learning pedagogy with practical SRL scaffolding in mathematics instruction. Schools should also strengthen pedagogical support, technology integration, instructional design, and collaborative professional learning. The IPMA results particularly identify DLR as an important priority for improvement because of its high importance and comparatively lower performance. At the policy level, these findings support coordinated implementation of deep learning that connects instructional readiness, student autonomy, and numeracy development. Such an approach is also relevant to broader educational priorities associated with Asta Cita and SDG 4. Overall, strengthening DLR and SRL simultaneously may provide a more sustainable pathway for improving students' numeracy literacy.

Limitations and Suggestions for Future Research

This study has several limitations that should be considered when interpreting the relationships among Deep Learning Readiness (DLR), Self-Regulated Learning (SRL), and Numeracy Literacy (NL). First, the cross-sectional correlational design limits the ability to establish causal relationships among the three constructs despite the significant structural pathways identified through PLS-SEM. Future studies should employ longitudinal or experimental designs to examine how changes in DLR and SRL influence numeracy literacy over time. Second, the participants were limited to 144 Grade VIII students from three junior secondary schools in Nganjuk Regency, which may restrict the generalizability of the findings to other educational contexts. Subsequent research should involve larger and more diverse samples across different regions, school types, and grade levels. Third, DLR and SRL were partly assessed through students' self-reported perceptions, which may be influenced by response tendencies and subjective judgments. Future studies could integrate teacher assessments, systematic classroom observations, learning analytics, and other behavioral measures to strengthen measurement triangulation. Fourth, although contextual data were obtained through classroom observations, focus group discussions, and document analysis, these data were not incorporated into the structural model. Further research could adopt mixed-methods designs to explain more deeply how classroom practices and institutional conditions shape the relationships identified quantitatively. Fifth, the current mediation model focused specifically on SRL, although other cognitive, motivational, and contextual mechanisms may also contribute to the relationship between DLR and numeracy literacy. Future studies could therefore extend the model by examining additional mediators or moderators, such as mathematical self-efficacy, motivation, metacognition, cognitive style, or socioeconomic context. Finally, intervention-based research is recommended to determine whether targeted improvements in deep learning readiness combined with explicit SRL scaffolding can produce sustained improvements in students' numeracy literacy.

CONCLUSION

This study examined the structural relationships among Deep Learning Readiness (DLR), Self-Regulated Learning (SRL), and Numeracy Literacy (NL) among 144 Grade VIII students in Indonesia. The findings showed that DLR significantly predicted SRL ($\beta = 0.512$) and NL ($\beta = 0.287$), while SRL significantly predicted NL ($\beta = 0.483$). The model explained 48.7% of the variance in NL, demonstrating the meaningful contribution of instructional readiness and learner regulation to numeracy outcomes. SRL also partially mediated the relationship between DLR and NL ($\beta = 0.247$; VAF = 46.3%), indicating that DLR is associated with numeracy literacy through both direct and self-regulatory pathways. These findings emphasize the importance of simultaneously strengthening pedagogical competence, technology integration, instructional design, school support, and SRL within mathematics instruction. This integrated approach can support educational priorities related to Asta Cita and SDG 4 by promoting meaningful learning, learner autonomy, and numeracy development. However, the cross-sectional design and purposive sample from three schools limit causal interpretation and broader generalization. Future studies should employ longitudinal or experimental designs with larger and more diverse samples. Multi-source measures of DLR involving students, teachers, classroom observations, and institutional evidence are also recommended. Further research could additionally compare the model across schools with different levels of deep learning implementation. Intervention studies are particularly needed to examine the effectiveness of integrating deep learning practices with explicit SRL scaffolding. Overall, the findings provide an empirical basis for developing integrated and scalable strategies to strengthen numeracy literacy in Indonesian junior secondary mathematics education.

AUTHOR CONTRIBUTIONS STATEMENT

Sherly Mayfana Panglinur Yekti contributed to conceptualization, methodology, investigation, data curation, formal analysis, original draft preparation, and project administration. Agustin Patmaningrum contributed to conceptualization, methodology, validation, formal analysis, and manuscript review and editing. Eny Dwi Utami contributed to methodology, validation, investigation, data interpretation, and manuscript review and editing. Nayla Sasti Ifadza contributed to investigation, data collection, data curation, visualization, and manuscript review and editing. Aditya Ramadhan contributed to investigation, resources, data curation, visualization, and manuscript review and editing. All authors contributed to the critical revision of the manuscript, approved the final version for publication, and agreed to be accountable for the integrity and accuracy of the work.

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