When Learning Readiness Fails to Predict Science Conceptual Understanding: Structural Evidence from Elementary Education in the Society 5.0 Era

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ABSTRACT

Aim. This study examines whether learning readiness functions primarily as a direct cognitive engine of science conceptual understanding or more strongly as an enabling behavioural infrastructure that supports students' participation in learning processes among fourth-grade students in the Society 5.0 context.

Methods. A quantitative explanatory design was employed. Data was collected from 320 Grade 4 students in public elementary schools and analysed using Partial Least Squares Structural Equation Modeling (PLS-SEM). The model integrates Learning Readiness, Digital Capability, Learning Motivation, and Self-Directed Learning as learning process constructs, and Science Conceptual Understanding as a higher-order cognitive construct reflected by Physical Changes, Force and Motion, and Life and Environment.

Result. The findings reveal a pronounced structural asymmetry. Learning Readiness strongly predicts Digital Capability, Learning Motivation, and Self-Directed Learning, explaining approximately 70–80% of the variance in learning behaviour, yet demonstrates negligible explanatory power for Science Conceptual Understanding. In contrast, Science Conceptual Understanding demonstrates strong internal coherence across its domains, indicating a stable higher-order cognitive structure. The findings further suggest that behavioural readiness alone may not be sufficient to directly support conceptual mastery under constrained digital and instructional conditions.

Conclusion. These results indicate that while learning readiness effectively shapes students' behavioural engagement in learning, conceptual understanding appears to depend more strongly on instructional quality, inquiry-oriented pedagogy, conceptual scaffolding, and pedagogically guided science learning experiences within elementary classrooms.

Cognitive value. This study repositions learning readiness not simply as a direct cognitive engine of conceptual mastery, but as an enabling behavioural infrastructure whose contribution to conceptual understanding may be shaped by broader instructional and pedagogical conditions in Society 5.0-oriented elementary science education.

Keywords: learning readiness, science conceptual understanding, PLS-SEM, Society 5.0, elementary science education

Introduction

The rapid acceleration of digital transformation has positioned education at the centre of societal adaptation in the Society 5.0 era. Unlike previous industrial revolutions that prioritised technological efficiency, Society 5.0 frames technology as a human-centred instrument for improving learning quality, inclusivity, and cognitive development (Althabhawi et al., 2022). Within this context, elementary education functions not only as a foundation for digital competence but also as a critical stage for developing students' reasoning and scientific understanding. However, despite major investments in digital infrastructure and learner readiness initiatives, an important question remains insufficiently explored: does learning readiness in digitally mediated environments directly translate into conceptual understanding in elementary science education?

Contemporary educational discourse increasingly positions learning readiness, digital capability, learning motivation, and self-directed learning as key predictors of success in technology-enhanced learning environments (Ahmed, 2023; Arviani et al., 2023). These constructs are widely assumed to strengthen motivation, autonomy, and technological confidence, thereby improving academic outcomes. Although this assumption has gained empirical support in higher education and adult contexts characterised by stable self-regulation and cognitive independence (Chien et al., 2022; Prihastiwi et al., 2024), its transferability to elementary education remains theoretically fragile and empirically underexplored, particularly in science learning where conceptual mastery requires systematic cognitive scaffolding.

Science education at the elementary level is epistemologically distinctive. Concepts such as force, motion, life systems, and physical change are not intuitively constructed through motivation or digital exposure alone (Gómez & Suárez, 2020; Putri et al., 2019). Instead, they require structured inquiry, guided experimentation, representational competence, and conceptually guided instructional support. Nevertheless, many contemporary policy narratives implicitly assume that strengthening readiness, motivation, and digital access is sufficient to improve conceptual learning outcomes. This assumption risks obscuring the distinction between learning behaviour and conceptual cognition, two developmental domains that may not evolve in parallel at the primary level.

Empirically, the global transition toward digital learning in elementary schools has revealed a marked asymmetry between behavioural engagement and conceptual depth. While students increasingly demonstrate activeness, autonomy, and digital familiarity, teachers in many contexts continue to struggle with the pedagogical integration of digital tools into concept-driven science instruction. Technology use frequently remains limited to presentation, task distribution, or assessment administration rather than functioning as a medium for conceptual modeling, inquiry facilitation, or scientific reasoning (Alonso-García et al., 2024; Chistyakov et al., 2023). This structural misalignment raises the possibility that learning readiness may optimise how students engage with learning systems without necessarily transforming what they understand conceptually.

From a theoretical standpoint, this condition exposes a significant gap in dominant readiness-based learning models. Existing frameworks commonly conceptualise readiness as a direct antecedent of learning performance, with digital capability, motivation, and self-directed learning positioned as central mechanisms associated with academic success (Ahmed, 2023; Gitadewi, 2024). However, these models are largely derived from adult learners and technology-rich environments. When applied to children, particularly in science learning, they may overestimate the direct cognitive contribution of readiness-related behaviour while underestimating the constitutive role of instruction, curriculum structure, and pedagogical support. Consequently, behavioural adaptability may be misinterpreted as equivalent to conceptual mastery.

Methodologically, existing research on readiness and digital learning predominantly relies on bivariate predictions, media comparisons, or direct-effect analyses, providing limited insight into how learning processes interact with conceptual outcomes. Few studies model Science Conceptual Understanding as a higher-order construct, and even fewer examine its relationship with readiness-driven learning processes in elementary contexts (Sarkam et al., 2022). As a result, the literature remains limited in explaining whether conceptual coherence in science emerges primarily from learner factors, instructional systems, or their interaction.

This limitation becomes increasingly important within the Society 5.0 paradigm, where readiness and digital confidence are frequently assumed to be sufficient drivers of learning transformation (Calp & Bütüner, 2022; Legi et al., 2023). Such assumptions risk prioritising psychological activation over pedagogical transformation, potentially producing adaptive and motivated learners without equivalent conceptual depth, particularly in primary education where misconceptions may persist over time.

Against this backdrop, the present study integrates learning readiness theory, digital learning processes, and elementary science conceptual systems through a PLS-SEM approach. Rather than treating Science Conceptual Understanding as a single outcome, the study models it as a higher-order cognitive system reflected through core science domains, enabling a more precise examination of its structural relationships and determinants. Conducted within the real constraints of elementary classrooms where digital instructional content remains limited, teachers continue adapting to shifting pedagogical expectations, and device access is uneven, this study examines whether readiness-driven learning processes function primarily as direct cognitive supports for conceptual understanding or more strongly as behavioural learning infrastructures shaped by instructional quality, conceptual scaffolding, and pedagogically guided science learning experiences.

Accordingly, this study addresses two central research questions. First, it examines how learning readiness and self-regulatory learning processes structurally interact with science conceptual understanding within a Society 5.0-oriented learning environment. Second, it evaluates the explanatory power and predictive quality of the proposed model to determine whether readiness-centered learning architectures meaningfully account for conceptual learning in elementary science.

By situating readiness within a developmental, pedagogical, and structural framework, this study contributes a corrective to adult-centric readiness models and offers a more instruction-sensitive interpretation of how conceptual understanding emerges in primary science learning. In doing so, it attempts to realign the discourse on digital transformation in education from a predominantly psychological and technological orientation toward a more pedagogical and epistemic perspective.

Literature Review

Learning Readiness as a Behavioural Infrastructure in Digital Learning Systems

Learning readiness has emerged as a multidimensional construct integrating learners' self-competence, technological capability, motivation, and self-regulatory capacity within technology-enhanced learning environments. Large-scale SEM evidence indicates that digital literacy functions as a major determinant of online learning readiness, with learner characteristics such as gender moderating these relationships (Itasanmi et al., 2025). These findings suggest that readiness extends beyond a psychological disposition and represents a technologically situated capability embedded within broader learner attributes. Furthermore, PLS-SEM studies demonstrate that psychological motivation and technological skills significantly shape e-learning readiness and indirectly influence downstream outcomes through its mediating role (Elshaer et al., 2025). Collectively, these findings position readiness as a central behavioural infrastructure within learning systems. However, existing models predominantly predict behavioural and attitudinal outcomes rather than domain-specific cognitive outcomes, leaving uncertainty regarding the extent to which readiness directly contributes to conceptual knowledge construction.

Self-Directed Learning as a Developmentally Embedded Construct

Furthermore, sequential mediation studies indicate that e-learning readiness operates within interconnected learning systems rather than as an independent determinant. Readiness, performance, and satisfaction function as mediators linking system quality with learners' willingness to sustain online learning, while motivation mediates the effects of technological skills, equipment capability, and user satisfaction on readiness itself (Ngah et al., 2022; Wagiran et al., 2022). Similar mediated patterns are observed across learning contexts, where readiness influences learning outcomes indirectly through engagement and emotional pathways rather than through direct effects (Ramos et al., 2025; Chien et al., 2022). Collectively, these findings position learning readiness as a behavioural and regulatory infrastructure rather than a direct cognitive determinant.

Similar tendencies are evident in self-directed learning research. Validation studies identify self-management, desire for learning, and self-control as core dimensions of self-directed learning readiness, although several dimensions demonstrate psychometric instability (Prabu Kumar et al., 2021). At younger developmental stages, self-directed learning readiness is strongly shaped by contextual and relational influences, including emotional intelligence, parenting, teaching style, and self-efficacy (Prihastiwi et al., 2024), while its contribution to competence remains mediated by the learning environment (Vasli & AsadiParvar-Masouleh, 2024). Together, these findings suggest that self-directed learning is developmentally and instructionally embedded rather than functioning as an independent cognitive engine.

Digital Capability, Learning Motivation, and the Process–Outcome Divide

Motivational and digital constructs have consistently been identified as important predictors of adaptive learning processes and affective outcomes. Learning motivation, self-efficacy, and self-directed learning readiness strongly predict online course satisfaction (Aisyah & Syarah, 2024), while goal orientation and perceived self-efficacy influence learning engagement and perceived teaching quality both directly and indirectly through online learning readiness (Ibrahim et al., 2022). Similarly, digital learning readiness, intrinsic motivation, and critical literacy significantly support students' engagement with smart learning systems in Society 5.0-oriented environments (Hidayat, Hidayah, et al., 2024). However, these studies predominantly focus on perceptual, behavioural, and process-oriented outcomes rather than domain-specific cognitive outcomes, indicating a persistent process–outcome divide. Furthermore, self-directed learning readiness, e-learning readiness, and learning motivation have been shown to operate as interconnected elements within a unified system rather than as independent predictors, further challenging the assumption that these constructs independently generate conceptual mastery.

Developmental and Pedagogical Constraints in Elementary Science Learning

Evidence from disrupted learning contexts further suggests that readiness-related variables require instructional mechanisms to generate meaningful learning experiences. Alternative assessment strategies have been shown to mediate the relationships among learning readiness, engagement, and motivation in shaping learning experiences (Ong et al., 2021), indicating that readiness alone is insufficient without pedagogical support. Similar patterns emerge among younger learners, where learning readiness is influenced more strongly by instructional and contextual factors than by learner characteristics alone. Academic supervision contributes to readiness primarily through teachers' pedagogical competence rather than professional competence, while self-directed learning readiness is significantly shaped by parenting and teaching styles (Prihastiwi et al., 2024). These findings suggest that younger learners require stronger external scaffolding and instructional guidance.

Research involving K–12 populations also remains largely teacher-centered. Studies on teachers' e-learning readiness reveal variations associated with demographic and technological factors (Polat et al., 2022), yet provide limited explanation regarding whether student readiness at the primary level follows similar structural patterns. This limitation highlights an important developmental gap in current readiness research.

Structural Gap Between Readiness Systems and Science Conceptual Understanding

Most existing structural models rarely incorporate domain-specific conceptual outcomes as higher-order constructs reflected by multiple disciplinary dimensions. Studies on readiness, motivation, and self-directed learning predominantly examine satisfaction, engagement, self-reported performance, or willingness to continue, which remain perceptual and process-oriented rather than cognitive and domain-specific. No studies within the reviewed literature model Science Conceptual Understanding as a higher-order construct reflected by Physical Changes, Force and Motion, and Life and Environment, nor examine whether readiness-driven learning processes predict such cognitive outcomes in elementary populations. This gap is theoretically significant in the Society 5.0 era, where psychological activation and digital exposure are frequently assumed to drive learning transformation.

Within this context, primary education continues to face persistent constraints related to device availability, digital pedagogical competence, curriculum rigidity, and institutional support. Although students increasingly demonstrate digital familiarity and behavioural readiness, science instruction remains largely teacher-centered and textbook-driven. Consequently, readiness and digital familiarity may sustain participation while failing to translate into conceptual transformation without inquiry-oriented pedagogical mediation.

Methods

This study employed a quantitative explanatory design using Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine the structural relationships among Learning Readiness, Digital Capability, Learning Motivation, Self-Directed Learning, and Science Conceptual Understanding within Society 5.0-oriented elementary science learning (Marliana et al., 2023). Data were analysed using SmartPLS 4 due to its suitability for hierarchical modeling, non-normal data distributions, bootstrapping procedures, and predictive educational research. To ensure transparency, reproducibility, and open-science compliance, all anonymised datasets and model outputs are publicly available via Figshare (DOI: 10.6084/m9.figshare.30727322).

The study was guided by two research questions. RQ1 asked: *How do the theoretical constructs of Learning Readiness, Digital Capability, Learning Motivation, Self-Directed Learning, and Science Conceptual Understanding interact within the proposed structural pathway model in the Society 5.0 learning context?* This question was addressed through the specification and examination of the hypothesised structural pathways among the latent constructs, with a particular focus on the conceptual alignment and directional logic of the SEM model. RQ2 asked: *To what extent does the proposed structural model demonstrate adequate explanatory power and predictive quality based on structural model evaluation indicators?* This question was addressed by evaluating the empirical results of the model, including path coefficients, statistical significance obtained through bootstrapping, and the coefficients of determination (R-square) for all endogenous constructs.

Population, Sample, and Sampling Technique

The population of this study consisted of fourth-grade students (Phase B) enrolled in public elementary schools (Sekolah Dasar Negeri) in Semarang, Indonesia. The total population comprised 320 students, representing all Grade 4 learners across the selected schools within the defined research setting.

A cluster sampling technique was employed, in which intact Grade 4 classrooms were selected as sampling units to preserve natural instructional conditions and maintain ecological validity. This approach was considered appropriate because students were organised in fixed classroom groups based on the official school structure, while the learning context was implemented at the classroom level.

The entire population of 320 students was included in the analysis, thereby minimising sampling bias and strengthening the generalisability of the findings within the study context. All participants were within the developmental range of Phase B, as defined by the national elementary education framework, and were actively engaged in science learning during the data collection period. Prior to data collection, formal permission was obtained from school authorities, and informed consent was secured from parents or legal guardians. Data collection was conducted during regular school hours under the supervision of classroom teachers to ensure standardised administration and ethical compliance.

Data Analysis Technique

This study employed structured instruments to measure all latent constructs in the proposed PLS-SEM model. Learning Readiness was operationalised through three reflective constructs, namely Digital Capability (DC), Learning Motivation and Attitude (LM), and Self-Directed Learning (SDL), measured using Likert-scale items. Science Conceptual Understanding was assessed using objective multiple-choice tests at the HOTS levels (C3–C5) and was modeled as a higher-order construct reflected by three first-order dimensions: Physical Changes (PC), Force and Motion (FM), and Life and Environment (LE). A complete description of all constructs, indicators, number of items, scale types, and operational definitions is presented in Appendix – Table A1. Data was analysed using Partial Least Squares Structural Equation Modeling (PLS-SEM) in SmartPLS version 4 based on the PLS Algorithm and Bootstrapping procedures. The analysis involved two stages: measurement model evaluation and structural model evaluation.

The measurement model assessed latent construct quality through outer loadings for indicator reliability, Composite Reliability and Cronbach's Alpha for internal consistency, and Average Variance Extracted (AVE) for convergent validity. Discriminant validity was examined using the Fornell–Larcker criterion. Digital Capability, Learning Motivation, and Self-Directed Learning were specified as reflective constructs, while Science Conceptual Understanding was modeled as a higher-order construct reflected by Physical Changes, Force and Motion, and Life and Environment.

The structural model was evaluated using path coefficients, T-statistics, P-values, and coefficients of determination (R-square and adjusted R-square) to assess the significance and explanatory power of the hypothesised relationships. The results were subsequently interpreted to examine the predictive role of Learning Readiness on Digital Capability, Learning Motivation, and Self-Directed Learning, as well as the contribution of Science Conceptual Understanding to students' mastery across the three science domains.

Results

RQ1: How do the theoretical constructs of Learning Readiness, Digital Capability, Learning Motivation, Self-Directed Learning, and Science Conceptual Understanding interact within the proposed structural pathway model in the Society 5.0 learning context? The structural pathway analysis reveals a clear functional separation among the core constructs in fourth-grade elementary students (Phase B). Learning Readiness operates as a foundational driver of students' digital capability, learning motivation, and self-directed learning, indicating its central role in shaping the self-regulatory learning system within the Society 5.0 context at the Grade 4 level. In contrast, Science Conceptual Understanding functions as a higher-order cognitive construct that directly governs students' mastery across the three science domains, namely Force and Motion, Life and Environment, and Physical Changes. Notably, the model does not support a direct structural link between Learning Readiness and Science Conceptual Understanding, suggesting that, for Grade 4 students, readiness primarily influences the process of learning rather than the immediate acquisition of scientific concepts.

Table 1
Main Information

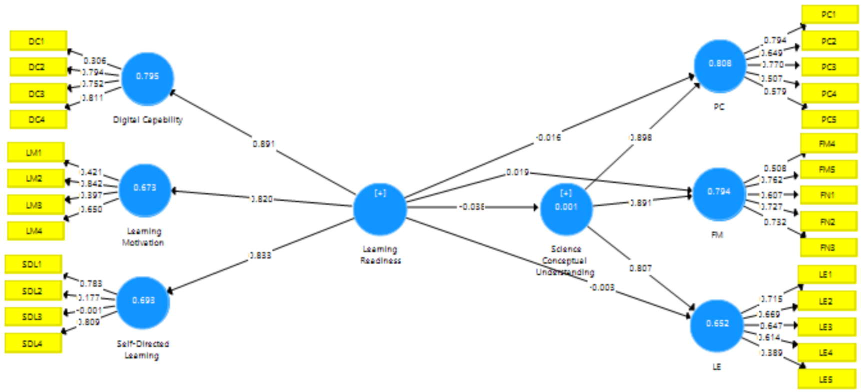
Description	Results
Population	Fourth-grade students (Phase B), public elementary schools
Research site	Semarang City, Indonesia
Sample size	320 students
Main predictor	Learning Readiness
Key mediated outcomes	Digital Capability, Learning Motivation, Self-Directed Learning
Higher-order outcome	Science Conceptual Understanding
Science domains	Force and Motion, Life and Environment, Physical Changes
Data availability	Figshare (DOI: 10.6084/m9.figshare.30727322)

Source. Own research.

Following the summary of the main study characteristics in the Main Information Table, the structural relationships among the latent constructs are presented through the PLS-SEM estimation. The initial structural configuration, path coefficients, and explained variance of each endogenous construct are first examined using the PLS Algorithm as shown below.

Figure 1

Sem PLS Algoritthm



Source. Own research.

Learning Readiness occupies a central position in the structural model and demonstrates strong predictive effects on all self-regulatory constructs, as presented in Figure 1. It strongly predicts Digital Capability (β = 0.891, R^2 = 0.795), Learning Motivation (β = 0.820, R^2 = 0.673), and Self-Directed Learning (β = 0.833, R^2 = 0.693), indicating its dominant role in shaping fourth-grade students' motivational and self-regulatory learning characteristics.

In contrast, Learning Readiness shows negligible relationships with science-related constructs, including Physical Changes (β = −0.016), Force and Motion (β = 0.019), Life and Environment (β = −0.003), and Science Conceptual Understanding (β = −0.038), with the latter demonstrating an extremely low explanatory power (R^2 = 0.001). These findings indicate that learning readiness contributes minimally to students' conceptual understanding of science.

Conversely, Science Conceptual Understanding demonstrates strong predictive effects across its three domains: Physical Changes (β = 0.898, R^2 = 0.808), Force and Motion (β = 0.891, R^2 = 0.794), and Life and Environment (β = 0.807, R^2 = 0.652). These relationships confirm its role as a higher-order construct that strongly organises students' conceptual performance across science domains.

The statistical significance of the structural relationships was confirmed through bootstrapping, as presented in Appendix (Figure A1). Learning Readiness demonstrates strong and significant effects on all self-regulatory constructs, including Digital Capability (T = 50.621), Learning Motivation (T = 42.471), and Self-Directed Learning (T = 43.800), confirming its role as a robust predictor of students' digital competence, motivation, and self-regulatory learning behaviour.

In contrast, Learning Readiness shows non-significant effects on Physical Changes (T = 0.644), Force and Motion (T = 0.553), Life and Environment (T = 1.078), and Science Conceptual Understanding (T = 0.842), indicating limited direct influence on students' science conceptual outcomes.

Conversely, Science Conceptual Understanding demonstrates strong and significant effects across all science domains, including Physical Changes (T = 33.388), Force and Motion (T = 72.801), and Life and Environment (T = 35.526). These findings provide strong support for its role as a higher-order construct governing students' performance across fourth-grade science domains.

Table 2

Interpretation of Outer Model

Indicator	Loading	AVE	CR	Cronbach's Alpha
DC1	0.306	0.487	0.775	0.621
DC2	0.794			
DC3	0.752			
DC4	0.811			
FM4	0.508	0.454	0.803	0.692
FM5	0.762			
FN1	0.607			
FN2	0.727			
FN3	0.732			
LE1	0.715	0.381	0.748	0.586
LE2	0.669			
LE3	0.647			
LE4	0.614			
LE5	0.389			
LM1	0.421	0.366	0.678	0.470
LM2	0.842			
LM3	0.397			
LM4	0.650			
PC1	0.794	0.447	0.798	0.684
PC2	0.649			
PC3	0.770			

Indicator	Loading	AVE	CR	Cronbach's Alpha
PC4	0.507			
PC5	0.579			
SDL1	0.783	0.325	0.536	0.179
SDL2	0.177			
SDL3	-0.001			
SDL4	0.809			

Source. Own research.

The measurement model evaluation, summarised in Table 2, reveals substantial variability in indicator performance across constructs. Several indicators meet the recommended loading threshold of 0.50, including DC2 (0.794), DC3 (0.752), and DC4 (0.811) for Digital Capability, as well as indicators within the Force and Motion, Physical Changes, and Life and Environment domains. However, several indicators show relatively low loading values, particularly DC1 (0.306), LM1 (0.421), LM3 (0.397), LE5 (0.389), SDL2 (0.177), and SDL3 (−0.001), indicating limited convergent representation in some constructs.

Composite Reliability values indicate acceptable internal consistency for Digital Capability (CR = 0.775), Force and Motion (CR = 0.803), and Physical Changes (CR = 0.798), whereas Learning Motivation (CR = 0.678) and Self-Directed Learning (CR = 0.536) remain below the recommended threshold. A similar pattern appears in Cronbach's Alpha, with relatively weak consistency particularly observed in Self-Directed Learning (0.179). In addition, Average Variance Extracted (AVE) values across all constructs remain below 0.50, suggesting limited convergent validity, especially among the self-regulatory variables.

Overall, the outer model results suggest that the structural relationships should be interpreted cautiously, particularly for Learning Motivation and Self-Directed Learning, which demonstrate relatively weak psychometric properties. Nevertheless, the science-related cognitive domains exhibit comparatively more stable measurement characteristics. Given these findings, additional attention was directed toward Science Conceptual Understanding, measured using dichotomously scored HOTS items. Because Cronbach's alpha may be limited for binary and multidimensional constructs, a dichotomous Rasch model was employed to strengthen evidence of reliability and item functioning (Andrich et al., 2012; Kreiner, 2012; Zubairi & Kassim, 2006).

Table 3

Summary of Rasch Measurement Statistics for HOTS Instrument

Component	Statistic	Person	Item
Reliability	Rasch Reliability	0.77–0.78	0.77–0.77–0.79

Component	Statistic	Person	Item
Separation	Separation Index	1.83–1.90	1.82–1.93
Fit Statistics	Mean Infit MNSQ	1.01	0.99
Fit Statistics	Mean Outfit MNSQ	1.00	1.00
Measurement Error	RMSE (Real)	0.72–0.82	0.29–0.31
Distribution	Mean Measure (logit)	0.23–0.43	0.00
Distribution	SD of Measure	1.31–1.49	0.56–0.57

Source. Own research.

To further examine the measurement quality of the HOTS instrument used to assess Science Conceptual Understanding, a Rasch analysis was conducted. The results indicate acceptable measurement reliability, with person reliability ranging from 0.77 to 0.78 and item reliability ranging from 0.77 to 0.79. Separation indices approaching 2.00 further suggest adequate precision in differentiating students' ability levels and calibrating item difficulty.

At the item level, most HOTS items function well within Rasch model expectations, with Infit and Outfit MNSQ values generally falling within the recommended range of 0.5–1.5, indicating consistent measurement of the intended cognitive construct. Although several items display elevated Outfit MNSQ values, these deviations remain within acceptable limits and do not indicate systematic item misfit.

Analysis of person fit further reveals that most respondents demonstrate response patterns consistent with model expectations, suggesting meaningful engagement with the HOTS items. A limited number of cases show unexpected response behaviour; however, these instances are sporadic and do not reflect pervasive response distortion.

The person-item map also indicates adequate alignment between student ability levels and item difficulty distribution. Most items are concentrated around the central range of the ability continuum, suggesting that the HOTS instrument is appropriately targeted to the cognitive characteristics of Grade 4 students. Items located at the lower and higher ends of the scale contribute to difficulty variation without creating substantial gaps in measurement coverage. Overall, the Rasch findings support the functional adequacy of the HOTS instrument and provide additional evidence that its measurement properties are sufficiently robust to support the subsequent structural model analysis.

RQ2: To what extent does the proposed structural model demonstrate adequate explanatory power and predictive quality based on structural model evaluation indicators?

Following the structural relationships presented in the previous section, the second research question focuses on evaluating the explanatory power of the proposed structural model. This evaluation aims to determine the extent to which the model explains the variance of each endogenous construct and to assess its overall predictive adequacy based on the available structural evaluation indicators

Table 4

Discriminant Validity

	Digital Capability	FM	LE	Learning Motivation	Learning Readiness	PC	Science Conceptual Understanding	Self-Directed Learning
Digital Capability	*0,698*							
FM	-0,028	*0,674*						
LE	-0,034	0,573	*0,617*					
Learning Motivation	0,564	-0,013	0,005	*0,605*				
Learning Readiness	0,891	-0,015	-0,033	0,820	*0,533*			
PC	-0,096	0,708	0,599	-0,011	-0,050	*0,669*		
Science Conceptual Understanding	-0,062	0,891	0,807	-0,009	-0,038	0,899	*0,568*	
Self-Directed Learning	0,613	0,013	-0,054	0,581	0,833	0,003	-0,011	*0,570*

Source. Own research.

Discriminant validity based on the Fornell–Larcker criterion is presented in Table 5. The diagonal values, representing the square roots of AVE, indicate moderate separation among most constructs; however, several inter-construct correlations approach or exceed these values, suggesting overlap among latent variables.

A particularly strong association is observed between Learning Readiness and Digital Capability (r = 0.891), exceeding the square roots of AVE for both Digital Capability (0.698) and Learning Readiness (0.533). A similar pattern appears between Learning Readiness and Self-Directed Learning (r = 0.833), indicating substantial conceptual and empirical overlap among readiness, digital confidence, and self-directed learning behaviour.

In contrast, Science Conceptual Understanding demonstrates theoretically consistent relationships with Force and Motion (0.891), Life and Environment (0.807), and Physical Changes (0.899), confirming their strong integration within the higher-order construct. Correlations between self-regulatory constructs and science domains remain generally low to moderate, suggesting partial separation between learning processes and cognitive outcomes. Overall, while the science constructs exhibit a coherent higher-order structure, discriminant validity among Learning Readiness, Digital Capability, and Self-Directed Learning remains limited, implying that these variables may represent closely intertwined dimensions of learning regulation among fourth-grade students.

Table 5
R Square

Construct	R Square	R Square Adjusted	Interpretation
Digital Capability	0.795	0.794	Strong
FM	0.794	0.792	Strong
LE	0.652	0.650	Moderate–Strong
Learning Motivation	0.673	0.672	Moderate–Strong
PC	0.808	0.807	Very Strong
Science Conceptual Understanding	0.001	-0.002	Very Weak
Self-Directed Learning	0.693	0.692	Moderate–Strong

Source. Own research.

The explanatory power of the structural model was evaluated using the coefficient of determination (R square and adjusted R square), as presented in Table 6. The model demonstrates strong explanatory power for several endogenous constructs. Digital Capability shows a high R square value of 0.795 (adjusted 0.794), indicating that Learning Readiness explains nearly 80 percent of the variance in students' digital capability. Similarly, Force and Motion records an R square of 0.794 (adjusted 0.792), reflecting the strong explanatory contribution of Science Conceptual Understanding to this science domain.

Moderate to strong explanatory power is also observed for Learning Motivation ($R^2 = 0.673$; adjusted 0.672), Life and Environment ($R^2 = 0.652$; adjusted 0.650), and Self-Directed Learning ($R^2 = 0.693$; adjusted 0.692). The highest explanatory power appears in Physical Changes ($R^2 = 0.808$; adjusted 0.807), indicating that Science Conceptual Understanding strongly explains students' achievement in this domain.

In contrast, the explanatory power for Science Conceptual Understanding itself is extremely weak ($R^2 = 0.001$; adjusted −0.002), indicating that the current structural specification does not adequately explain students' overall science conceptual understanding, despite its strong predictive effects across all three science domains. This pattern suggests that additional factors beyond the present model are likely involved in shaping conceptual understanding at the fourth-grade level. To further examine whether the proposed structural relationships are statistically supported, significance testing through bootstrapping is presented in Appendix (Table A2).

The statistical significance of the structural relationships is summarised in Table 7. Learning Readiness demonstrates strong and significant effects on Digital Capability ($\beta = 0.891$, $T = 54.959$, $p = 0.000$), Learning Motivation ($\beta = 0.820$, $T = 40.517$, $p = 0.000$), and Self-Directed Learning ($\beta = 0.833$, $T = 42.119$, $p = 0.000$), confirming its central role in shaping students' motivational and self-regulatory learning characteristics.

In contrast, Learning Readiness shows non-significant effects on Force and Motion ($\beta = 0.019$, $T = 0.794$, $p = 0.428$), Life and Environment ($\beta = -0.003$, $T = 0.082$, $p = 0.935$), Physical Changes ($\beta = -0.016$, $T = 0.659$, $p = 0.510$), and Science Conceptual Understanding ($\beta = -0.038$, $T = 0.614$, $p = 0.540$), suggesting that readiness influences learning processes rather than directly affecting science conceptual outcomes. Conversely, Science Conceptual Understanding demonstrates strong and significant effects across all science domains, including Force and Motion ($\beta = 0.891$, $T = 68.120$, $p = 0.000$), Life and Environment ($\beta = 0.807$, $T = 38.338$, $p = 0.000$), and Physical Changes ($\beta = 0.898$, $T = 88.776$, $p = 0.000$). These findings provide strong support for its role as a higher-order construct governing students' achievement across fourth-grade science domains.

Discussion

Key Finding

This study reveals a highly asymmetric structural pattern between learning process variables and cognitive outcomes among fourth-grade students in the Society 5.0 context. Learning Readiness emerges as a strong predictor of Digital Capability ($\beta = 0.891$; $R^2 = 0.795$), Learning Motivation ($\beta = 0.820$; $R^2 = 0.673$), and Self-Directed Learning ($\beta = 0.833$; $R^2 = 0.693$), explaining nearly 70–80 percent of the variance in students' motivational, regulatory, and digital learning behaviour. These findings reflect classroom conditions in which, despite limited digital infrastructure, students who are cognitively and behaviourally ready to learn tend to demonstrate higher levels of activity, independence, and motivation regardless of device availability.

However, a critical rupture emerges at the level of Science Conceptual Understanding. Despite the strong behavioural effects of Learning Readiness, its explanatory power for Science Conceptual Understanding remains virtually negligible ($\beta = -0.038$; $p = 0.540$; $R^2 = 0.001$). Importantly, this non-significant relationship cannot be attributed to measurement weakness, as the HOTS-based Science Conceptual Understanding construct demonstrates acceptable reliability and item functioning under Rasch analysis. Rather, the finding becomes more intelligible within the actual instructional context, where digital integration in science learning remains constrained by teachers' limited capacity to design conceptually rich and inquiry-oriented learning experiences. Under such conditions, readiness, motivation, and self-direction may optimise students' engagement behaviour, yet their translation into conceptual understanding appears to depend more strongly on instructional quality, inquiry-oriented pedagogy, conceptual scaffolding, and pedagogically guided scientific reasoning. Accordingly, pedagogical mediation in this study is interpreted not as an empirically tested SEM mediator, but as a contextual instructional condition shaping how readiness-related learning behaviours contribute to conceptual understanding outcomes.

Once Science Conceptual Understanding is established, however, its internal structure proves to be exceptionally strong. The construct exerts very high predictive effects on Physical Changes ($\beta = 0.898$; $R^2 = 0.808$), Force and Motion ($\beta = 0.891$; $R^2 = 0.794$), and Life and Environment ($\beta = 0.807$; $R^2 = 0.652$). These results demonstrate that science understanding among fourth-grade students functions as a coherent higher-order cognitive system rather than as fragmented, topic-specific knowledge. The Rasch analysis further reinforces this interpretation by indicating that the HOTS items are well targeted to students' ability levels and operate consistently across domains, strengthening confidence in the observed structural coherence.

From a psychometric and developmental perspective, although Learning Motivation and Self-Directed Learning display strong structural relationships, their relatively weak reliability and convergent validity suggest that these constructs are developmentally fluid rather than substantively deficient. This aligns with classroom realities in which fourth-grade students may exhibit high motivation and independence in observable behaviour, while their self-regulatory capacities remain situational and strongly shaped by task design and teacher guidance. Consequently, the observed weaknesses in the outer model should be interpreted as limitations of self-report measurement at the primary level rather than as deficits in students' learning potential.

The discriminant validity results further sharpen this interpretation. The strong empirical overlap between Learning Readiness and Digital Capability ($r = 0.891$), as well as between Learning Readiness and Self-Directed Learning ($r = 0.833$), reflects the developmental reality that readiness in elementary students is primarily expressed through initiative, persistence, and willingness to engage in learning activities rather than through stable technological competence. In contexts where access to digital devices is uneven, readiness operates as a behavioural disposition that enables participation, not as a direct driver of conceptual mastery. At this stage, readiness, autonomy, and engagement therefore function as an integrated adaptive system rather than as sharply differentiated constructs.

Taken together, these findings suggest that Learning Readiness may function less as a direct cognitive engine of science understanding and more as an enabling behavioural infrastructure that supports students' participation in learning under constrained digital conditions. At the same time, Science Conceptual Understanding emerges as a pedagogically constructed cognitive system whose development appears to depend strongly on instructional quality, conceptual scaffolding, and inquiry-oriented pedagogical support within the classroom context (Mukaromah et al., 2024). In this sense, the findings highlight the importance of strengthening teachers' digital pedagogical competence and conceptually guided science instruction to ensure that behavioural readiness is accompanied by meaningful conceptual development in the Society 5.0 learning environment.

Comparasion with Previous Study

Previous SEM-based studies in higher education and HyFlex contexts consistently identify learning readiness as a significant predictor of learning performance and outcomes. Digital literacy strongly predicts online learning readiness (Itasanmi et al., 2025), while e-learning readiness has been shown to influence learning performance directly and indirectly through engagement mechanisms (Ramos et al., 2025). In contrast, the present study reveals a different structural pattern at the fourth-grade level. Although Learning Readiness strongly predicts Digital Capability, Learning Motivation, and Self-Directed Learning (β = 0.820–0.891), it shows no significant direct effect on Science Conceptual Understanding ($\beta = -0.038$; $R^2 = 0.001$). This divergence suggests a developmental boundary of the readiness–performance paradigm, where readiness functions as a behavioural and regulatory infrastructure rather than a direct cognitive driver in children.

Similar evidence from AI-driven learning environments further suggests that readiness in higher education is strongly associated with technological systems and learning efficiency (Alshammari & Alshammari, 2022). However, unlike these contexts, the present findings demonstrate that strong readiness and digital capability do not necessarily translate into science conceptual mastery at the elementary level. This indicates that conceptual understanding in primary education may depend more strongly on domain-specific instructional mediation than on readiness alone. Collectively, these findings suggest that readiness models derived from higher education and HyFlex environments cannot be directly generalised to elementary science contexts (Ibrahim et al., 2022), as readiness at the primary level appears to support learning regulation and adaptation rather than conceptual development itself.

Implication for Practice and Theory Implication for Practice and Theory

This study offers practical guidance for primary science education by demonstrating that Learning Readiness strongly strengthens digital capability, motivation, and self-directed learning, yet does not directly shape science conceptual understanding. This implies that instructional mediation, conceptual scaffolding, and inquiry-based pedagogy must be ualongside readiness development within the Society 5.0 context. Teacher pedagogical competence and curriculum alignment thus become central levers of conceptual learning. Theoretically, the findings reposition learning readiness as a behavioural-regulatory infrastructure rather than a direct cognitive determinant. The structural autonomy of science conceptual understanding calls for hybrid theoretical models that integrate self-regulation, instructional design, and domain-specific cognitive mediation in elementary education.

Limitation of This Study

This study acknowledges several limitations that warrant further theoretical and methodological development. First, the cross-sectional SEM design limits the ability to capture the developmental dynamics between learning readiness and science conceptual understanding over time; therefore, the identified structural relationships should be interpreted within a contemporaneous explanatory framework rather than as stable developmental trajectories. Second, the use of self-report instruments for motivational and self-regulatory constructs may partly explain the relatively weak convergent validity and reliability observed in several indicators, particularly in primary education contexts where motivation, autonomy, and self-direction remain situational and strongly shaped by instructional guidance. In addition, although this study identified a highly asymmetric relationship between behavioural learning variables and science conceptual understanding, pedagogical and instructional processes were not directly operationalised as empirically tested constructs within the SEM model.

Consequently, pedagogical mediation should be interpreted as a theoretically informed contextual explanation rather than a statistically verified mediating mechanism. The negligible explanatory power of Learning Readiness for Science Conceptual Understanding suggests that conceptual mastery in elementary science learning may depend more strongly on instructional quality, inquiry-oriented pedagogy, conceptual scaffolding, and teacher digital competence than on readiness-related behavioural engagement alone. Furthermore, the focus on Grade 4 students within a single urban context limits broader generalisation across developmental stages and educational settings. Future studies are therefore encouraged to incorporate pedagogical variables explicitly, employ complementary analytical approaches such as generalised linear modeling and multilevel instructional models, and conduct comparative longitudinal investigations across diverse Society 5.0 learning environments.

Conclussion

This study provides empirical evidence that Learning Readiness functions as a powerful regulator of elementary students' learning behaviour, strongly shaping Digital Capability, Learning Motivation, and Self-Directed Learning within the Society 5.0 context. However, Learning Readiness demonstrates negligible explanatory power for Science Conceptual Understanding, challenging the dominant readiness–performance assumption commonly supported in adult and higher education research. Conversely, Science Conceptual Understanding emerges as a coherent higher-order cognitive system exerting strong effects on Physical Changes, Force and Motion, and Life and Environment, indicating that conceptual mastery in elementary science depends more strongly on pedagogical mediation and domain-specific cognitive scaffolding than on psychological readiness alone. The strong overlap among readiness, digital capability, and self-directed learning further suggests that these constructs operate as an integrated adaptive disposition in children. Collectively, these findings advance a developmentally grounded reconceptualisation of learning readiness as a behavioural-regulatory infrastructure rather than a direct cognitive engine, while reaffirming instructional quality as a central mechanism for conceptual learning in the Society 5.0 era.

Declaration of the Use of AI

During the preparation of this work, the author(s) used ChatGPT (OpenAI), and QuillBot to improve the readability, coherence, and language clarity of the manuscript. All content generated with these tools was critically reviewed, revised, and edited by the author(s), who take full responsibility for the integrity, accuracy, and originality of the final published article.

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Appendix

Table A1

Variable Canstruct Testing

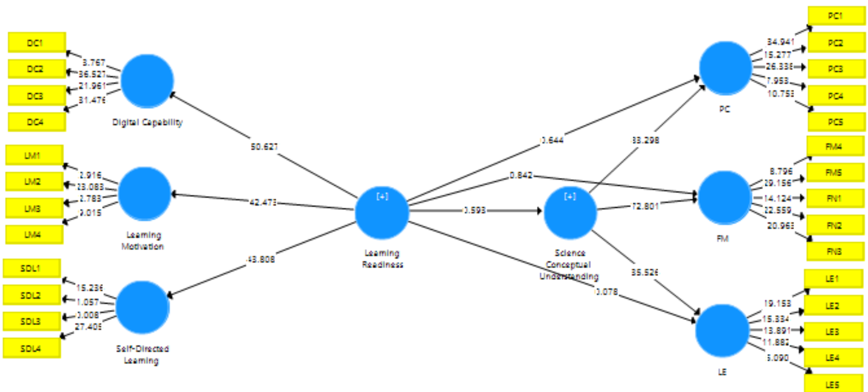
Variable	Indicator	Code	Number of Items	Scale Type	Description
Learning Readiness	Digital Capability (DC)	DC1–DC4	4	Likert 1–5	Students' ability and confidence in using digital devices and learning technologies to support learning activities.
	Learning Motivation & Attitude (LM)	LM1–LM4	4	Likert 1–5	Students' motivation, interest, persistence, and positive emotional attitude toward learning activities.
	Self-Directed Learning (SDL)	SDL1–SDL4	4	Likert 1–5	Students' ability to plan, monitor, and evaluate their own learning independently.

Variable	Indicator	Code	Number of Items	Scale Type	Description
Science Conceptual Understanding	Physical Changes (PC)	PC1–PC5	5	Multiple choice (HOTS C3–C5)	Students' understanding of physical changes, including melting, evaporation, condensation, and heat transfer.
	Force & Motion (FM)	FM1–FM5	5	Multiple choice (HOTS C3–C5)	Students' ability to analyse force, motion, friction, and the effects of mass on movement.
	Life & Environment (LE)	LE1–LE5	5	Multiple choice (HOTS C3–C5)	Students' understanding of living systems, adaptation, environmental interaction, and the importance of natural cycles.

Source. Own research.

Figure A1

Sem PLS Boostrapping



Source. Own research.

Table A2

Structural Path Significance

Structural Path Significance	Original Sample (O)	T Statistics (O/STDEV)	P Values	Interpretation
Learning Readiness → Digital Capability	0,891	54,959	0,000	Significant
Learning Readiness → FM	0,019	0,794	0,428	Not Significant
Learning Readiness → LE	-0,003	0,082	0,935	Not Significant
Learning Readiness → Learning Motivation	0,82	40,517	0,000	Significant

Structural Path Significance	**Original Sample (O)**	**T Statistics (O/STDEV)**	**P Values**	**Interpretation**
Learning Readiness → PC	-0,016	0,659	0,51	Not Significant
Learning Readiness → Science Conceptual Understanding	-0,038	0,614	0,54	Not Significant
Learning Readiness → Self-Directed Learning	0,833	42,119	0,000	Significant
Science Conceptual Understanding → FM	0,891	68,12	0,000	Significant
Science Conceptual Understanding → LE	0,807	38,338	0,000	Significant
Science Conceptual Understanding → PC	0,898	88,776	0,000	Significant

Source. Own research.