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Weaknesses in Basic Math Skills Non-Numerate Learners in Key Stage 2 Using Cognitive Diagnostic Modeling

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ABSTRACT

This study applied Cognitive Diagnostic Modeling (CDM) to identify the specific basic mathematics attributes underlying non-numeracy among purposively selected Grades 4 to 6 learners in public elementary schools of the Paniqui West District. A quantitative, non-experimental diagnostic design was used. Learners identified as performing in the lowest quartile of a curriculum-based numeracy assessment completed a researcher-developed Diagnostic Numeracy Assessment linked to an expert-validated Q-matrix. Item-level responses were analyzed through the G-DINA model, mastery/non-mastery classification, Latent Class Analysis, hierarchical dependency testing, and concordance analysis using Cohen's Kappa. The highest non-mastery rates occurred in Subtraction with Regrouping (78.5%) and Addition with Regrouping (71.2%), while Place Value was not mastered by 62.1% of the learners. Latent Class Analysis identified a Basic Facts Master profile as the largest group (39.5%), followed by a Global Deficit profile (28.1%) and a Regrouping Barrier profile (18.9%). Hierarchical testing confirmed that Place Value was a significant prerequisite for Addition with Regrouping (Chi-square = 15.90, $p < .001$) and that Single-Digit Subtraction was a prerequisite for Subtraction with Regrouping (Chi-square = 25.43, $p < .001$). Agreement between CDM and traditional total-score classifications was only moderate (Kappa = 0.45), with a combined misclassification rate of 28.8%. The findings show that conventional total scores conceal distinct cognitive deficits and that remediation should follow the demonstrated skill hierarchy, beginning with place value and basic subtraction before advancing to regrouping. CDM provides a more precise basis for differentiated and evidence-based numeracy intervention.

Keywords: *cognitive diagnostic modeling, non-numerate learners, place value, regrouping, latent class analysis, Key Stage 2*

INTRODUCTION

Foundational numeracy is essential for academic progression, problem-solving, and participation in daily life. By Key Stage 2, learners are expected to have developed number recognition, place-value understanding, fact fluency, and the ability to perform multi-digit operations. When these foundational competencies remain weak, later mathematics becomes increasingly difficult because new procedures depend on knowledge that has not yet been secured. Stable low-skill trajectories from the middle elementary grades illustrate how early gaps can persist without precise intervention (Kilp-Kabel & Mädamürk, 2024).

Mathematics difficulty is rarely uniform. Learners may have generalized deficits across number concepts and operations, or they may demonstrate strong basic facts but fail when tasks require regrouping, multiple steps, or language-heavy problem solving. Muñez et al. (2023) identified distinct subgroups among children at risk for mathematics learning difficulties, while Cheung et al. (2023) showed that working memory, fact fluency, and mathematics anxiety affect performance differently across task conditions. These findings indicate that a single total score cannot adequately explain why a learner fails.

Traditional assessments generally classify learners as passing or failing based on the sum of correct answers. Although useful for broad screening, such scores may obscure the underlying cognitive attributes needed to solve each item. Wray and Reynolds (2025) found that a widely used diagnostic assessment largely reflected general mathematics ability rather than clearly differentiated subskills. Cognitive Diagnostic Modeling addresses this limitation by linking test items to a Q-matrix and estimating mastery or non-mastery of fine-grained attributes, thereby producing an interpretable cognitive profile for each learner.

The need for a more precise diagnostic approach is particularly important in public elementary schools where instructional time and remediation resources are limited. Broad reteaching may spend time on skills that learners have already mastered while failing to address the true prerequisite deficit. In the Paniqui West District, non-numerate Grades 4 to 6 learners required an assessment approach capable of identifying their most frequently missing attributes, grouping them according to mastery patterns, testing prerequisite relationships among skills, and comparing these results with conventional total-score classifications.

This study therefore investigated weaknesses in basic mathematics skills among non-numerate Key Stage 2 learners using CDM. It determined the most frequently lacking cognitive attributes, identified prevalent latent mastery profiles, examined significant hierarchical dependencies among attributes, and assessed the agreement between CDM classifications and traditional total-score results. The study provides a basis for precision remediation in which instructional content, sequence, and intensity are aligned with the learner's actual cognitive profile rather than with a general label of low achievement.

Literature Review

Foundational Numeracy and Persistent Skill Gaps

Mathematics knowledge develops cumulatively, with later concepts depending on the mastery and automatic retrieval of earlier skills. Learners who do not establish number sense, place value, and basic operations are likely to experience increasing difficulty as tasks become more complex. Kilp-Kabel and Mädamürk (2024) reported stable low, average, and high mathematics trajectories across Grades 3 and 5, suggesting that early difficulties tend to persist when instruction does not directly address the missing foundation.

Research also shows that struggling learners are heterogeneous. Muñez et al. (2023) distinguished children with broad mathematical weaknesses from those whose difficulty was concentrated in arithmetic fluency. Bernabini et al. (2021) found that children's own symbolic numerical processing was a stronger predictor of mathematics achievement than parental skill alone. These findings support diagnostic approaches that identify the particular knowledge components a learner has or has not mastered rather than treating all low-performing learners as one group.

Domain-specific proficiency is especially important. Hall et al. (2023) found that handwriting fluency did not significantly predict mathematics computation after basic fact fluency was considered, while Fyfe and Borriello (2025) cautioned that training general cognitive skills rarely transfers reliably to mathematics achievement. Direct assessment and instruction of foundational mathematics attributes are therefore more likely to improve performance than broad interventions that are not linked to the learner's actual deficit.

Cognitive Load, Affective Factors, and Task Complexity

Cognitive Load Theory explains why multi-step mathematical procedures become difficult when foundational schemas are incomplete. Working memory has limited capacity; therefore, learners who must consciously reconstruct basic facts or place-value relationships have fewer resources available for carrying, borrowing, and monitoring a sequence of operations (Sweller, 1988). Cheung et al. (2023) demonstrated that executive functioning and mathematics anxiety contribute differently to timed and untimed computation, emphasizing the interaction between task demand and cognitive capacity.

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Instructional design can either reduce or intensify cognitive load. The Concrete-Representational-Abstract sequence uses manipulatives, visual models, and symbols in a progressive manner that supports schema formation. Kaya and Yildiz (2024) reported the effectiveness of this sequence in teaching mathematics to a learner with autism in a general education classroom. Worked examples, guided practice, systematic repetition, and explicit sequencing likewise help learners automate lower-level skills before facing more complex procedures (Adams & Maki, 2023; Hardy, 2025).

Language and affective demands may add extraneous load. Kwok and Kwan (2025) noted that students' ability to solve word problems is influenced by linguistic complexity, while Wei et al. (2023) found differences between autistic students and their peers in performance, response time, and enjoyment. Hamidi et al. (2024) further showed the value of integrating reading strategies and working-memory support in elementary mathematics. Diagnostic information must therefore be interpreted alongside the conditions under which learners perform.

Cognitive Diagnostic Modeling and Skill Profiles

CDM differs from conventional testing because it estimates mastery of explicitly defined cognitive attributes. Each assessment item is linked through a Q-matrix to the knowledge and procedures needed for a correct response. The resulting mastery profile provides a cognitive map rather than a single achievement score. This level of detail is especially useful when learners obtain similar total scores for different reasons, such as weak place value, slow fact retrieval, or failure to coordinate multiple steps.

Latent Class Analysis complements CDM by identifying recurring mastery patterns across learners. Such profiles allow teachers to distinguish a global deficit from a narrow procedural barrier and to assign intervention accordingly. The heterogeneity documented by Muñez et al. (2023) supports this profile-based approach, while Silver et al. (2024) showed that the benefits of mathematics activities depend on the skills children already possess. Intervention is most efficient when it begins from the learner's demonstrated entry point.

More granular diagnosis is also important for assessment validity. Wray and Reynolds (2025) questioned whether broad diagnostic tests isolate distinct mathematics subskills adequately. Mpuangnan (2024) emphasized the importance of teacher competence in constructing valid test items. In CDM, an expert-validated Q-matrix and carefully designed items are essential because inaccurate links between items and attributes can lead to incorrect mastery classifications. The quality of the diagnostic inference depends on the quality of both the assessment and its cognitive specification.

Hierarchical Learning Trajectories and Precision Remediation

Hierarchical Learning Trajectories view mathematics as a structured sequence in which prerequisite skills support more advanced competencies. Place value, for example, enables learners to understand why a digit can be decomposed and exchanged during regrouping. Basic subtraction is likewise necessary before borrowing can be coordinated across columns. A learner who has not mastered these prerequisites may imitate a procedure temporarily but cannot sustain accurate performance across varied items.

Instruction that follows the hierarchy can reduce cognitive overload and strengthen conceptual understanding. The Concrete-Representational-Abstract sequence is consistent with this principle because it rebuilds knowledge from concrete quantity relationships to symbolic procedures (Kaya & Yildiz, 2024). Adams and Maki (2023) showed that systematic drill can improve multiplication fluency, but such practice is most useful when it targets a confirmed gap. Direct, sequenced instruction is preferable to indiscriminate repetition.

The hierarchy also supports differentiated intervention and prevention. Early digital assessment can identify modifiable numeracy skills before deficits widen (Navarrete-Ulloa et al., 2025), while parent support is most effective when matched to the child's current skill level (Ribeiro et al., 2024). Attaway et al. (2025) highlighted the importance of understanding the actual content and structure of classroom mathematics instruction. Together, these studies indicate that diagnostic precision, developmentally ordered teaching, and context-sensitive support are necessary for sustainable numeracy improvement.

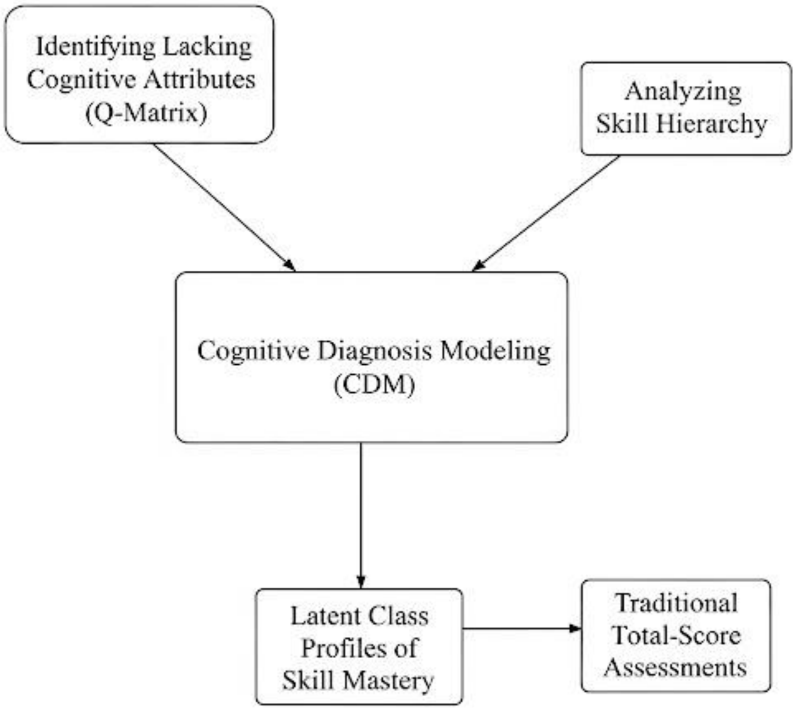

Figure 1. *Conceptual framework of the study*

METHODS

Research Design

The study employed a quantitative, non-experimental diagnostic design centered on Cognitive Diagnostic Modeling. The design was appropriate because it enabled the researcher to estimate mastery and non-mastery of specific mathematical attributes from item-level response patterns, classify learners into interpretable profiles, examine prerequisite relationships among attributes, and compare CDM classifications with traditional total-score results. No variables were manipulated, and the assessment was administered within the learners' natural school setting.

Research Locale

The research was conducted in public elementary schools of the Paniqui West District. The district was selected because it served a diverse Key Stage 2 population and had identified a need for more precise diagnostic information for learners experiencing persistent numeracy difficulty. Cooperation from district officials, school heads, and mathematics coordinators facilitated participant identification and standardized assessment administration.

Participants and Sampling Technique

Purposive, criterion-based sampling was used to select Grades 4 to 6 learners identified as non-numerate. In collaboration with mathematics teachers, potential participants were screened using standardized or curriculum-based assessments and classroom performance records. Learners who performed in the lowest quartile and

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demonstrated persistent difficulty in foundational numeracy were included. The source manuscript specified a target range of approximately 150 to 200 learners to support stable CDM parameter estimation and meaningful latent-class identification.

Research Instrument

The primary instrument was a researcher-developed Diagnostic Numeracy Assessment designed to measure eight fine-grained attributes: Number Identification (A1), Place Value (A2), Single-Digit Addition (A3), Addition with Regrouping (A4), Single-Digit Subtraction (A5), Subtraction with Regrouping (A6), Basic Multiplication (A7), and Basic Division (A8). Unlike a conventional test intended only to generate a total score, each item was constructed to require a defined combination of cognitive attributes.

An expert-validated Q-matrix served as the formal specification linking each item to the attributes required for a correct answer. Mathematics education specialists reviewed the content, cognitive demands, and item-attribute mapping. The matrix used binary entries to indicate whether each attribute was required by each item and provided the basis for estimating individual mastery probabilities through CDM.

Data Gathering Procedure

After securing institutional permission and parental consent, the researcher coordinated with participating schools and administered the Diagnostic Numeracy Assessment under standardized, group-based conditions. Learners received age-appropriate instructions and were informed that the activity was not a graded classroom examination. Completed response sheets were coded anonymously, checked for completeness, and encoded as dichotomous item responses for analysis.

Data Analysis

The G-DINA model was fitted to the item-response data using the GDINA package in R. Model evaluation considered indices such as the Akaike Information Criterion and Bayesian Information Criterion. Attribute-level mastery probabilities and dichotomous mastery classifications were generated to determine non-mastery prevalence. Latent Class Analysis was then applied to identify recurring profiles of mastered and non-mastered attributes.

Hierarchical dependency testing examined whether mastery of selected prerequisite skills was significantly associated with mastery of more complex skills. Wald Chi-square statistics and p-values were used to evaluate the proposed dependencies. Finally, concordance analysis compared CDM classifications with classifications based on traditional total scores. Simple agreement, Cohen's Kappa, false-positive rates, and false-negative rates were computed.

Ethical Considerations

The study observed heightened safeguards because the participants were children identified as struggling learners. Permission was obtained from district and school authorities, written informed consent was secured from parents or guardians, and learner assent was obtained using age-appropriate explanations. Participation was voluntary, and learners could withdraw without penalty.

To prevent stigma, all records used participant codes, and findings were reported only in aggregate. The assessment was administered in a supportive, low-stakes environment to reduce anxiety. Data were stored securely and used only for research purposes. Aggregated diagnostic findings were intended to support school-level intervention planning and the principle of beneficence.

RESULTS AND DISCUSSION

Frequently Lacking Cognitive Attributes

Table 1. *Non-mastery prevalence of the eight basic mathematics attributes*

Attribute	Description	Non-Mastery	SE	Rank
A6	Subtraction with Regrouping	78.5%	3.1%	1
A4	Addition with Regrouping	71.2%	3.5%	2
A2	Place Value	62.1%	4.2%	3
A8	Basic Division	55.4%	4.8%	4
A7	Basic Multiplication	49.3%	5.1%	5
A5	Single-Digit Subtraction	35.8%	3.9%	6
A3	Single-Digit Addition	22.0%	3.2%	7
A1	Number Identification	10.5%	2.5%	8

The most serious weaknesses were concentrated in regrouping. Subtraction with Regrouping (A6) had the highest non-mastery prevalence at 78.5%, followed by Addition with Regrouping (A4) at 71.2%. Place Value (A2) was not mastered by 62.1% of learners, revealing a conceptual foundation that was too weak to support exchanges across ones, tens, and higher place values. In contrast, Number Identification (10.5%) and Single-Digit Addition (22.0%) were comparatively secure.

This pattern indicates that many learners had acquired basic recognition and simple fact knowledge but could not coordinate place-value concepts with multi-step procedures. Under Cognitive Load Theory, such learners must devote excessive working-memory resources to reconstructing the meaning of each digit while also remembering a carrying or borrowing step. The result is procedural breakdown. The finding supports direct work on conceptual place value before repeated practice in regrouping and is consistent with evidence that mathematics intervention should target domain-specific foundations rather than rely on general cognitive training (Fyfe & Borriello, 2025; Hall et al., 2023).

Latent Mastery and Non-Mastery Profiles

Table 2. *Prevalent learner profiles identified through Latent Class Analysis*

Class	Mastery Pattern	Prevalence	Interpretation
Class 1	Mastery: A1, A2, A3, A5; non-mastery: A4, A6, A7, A8	39.5%	Basic Facts Master
Class 2	Non-Mastery: A1-A8	28.1%	Global Deficit
Class 3	Mastery: A1, A2, A3, A5, A7, A8; non-mastery: A4, A6	18.9%	Regrouping Barrier
Remaining	Various less frequent profiles	13.5%	Lower-Prevalence Profiles

The largest latent class, representing 39.5% of the sample, was the Basic Facts Master profile. These learners had mastered number identification, place value, and simple addition and subtraction but had not mastered regrouping, multiplication, or division. The second class, the Global Deficit profile, comprised 28.1% and showed non-mastery across all eight attributes. The Regrouping Barrier profile accounted for 18.9% and was distinguished by mastery of nearly all basic skills except addition and subtraction with regrouping.

The profiles demonstrate why a single remedial program is inappropriate. Learners in the Global Deficit group require intensive rebuilding from number identification and early number concepts, whereas the Regrouping Barrier group requires a narrow conceptual and procedural intervention. The largest group needs targeted support in multi-step operations rather than complete reteaching of basic facts. This result parallels the heterogeneity identified by Muñez et al. (2023) and supports Silver et al.'s (2024) conclusion that the value of an instructional activity depends on the skills learners bring to it.

Hierarchical Dependencies Among Mathematical Attributes

Table 3. *Tests of proposed prerequisite relationships*

Dependency	Wald Chi-square	df	p-value	Conclusion
A3 -> A4	1.85	1	.174	Not significant
A2 -> A4	15.90	1	< .001	Significant prerequisite
A5 -> A6	25.43	1	< .001	Significant prerequisite

The proposed dependency from Single-Digit Addition to Addition with Regrouping (A3 -> A4) was not statistically significant, $p = .174$. However, Place Value was a significant prerequisite for Addition with Regrouping (A2 -> A4), Chi-square = 15.90, $p < .001$. Single-Digit Subtraction was also a significant prerequisite for Subtraction with Regrouping (A5 -> A6), Chi-square = 25.43, $p < .001$.

These findings show that instructional sequence should be based on the cognitive structure of the task rather than on a rigid calendar. Addition with regrouping depends more fundamentally on understanding the value and exchangeability of digits than on simple addition alone. Subtraction with regrouping requires both the meaning of subtraction and the ability to coordinate the borrowing procedure. The demonstrated dependencies support Hierarchical Learning Trajectories and the use of concrete and representational models before abstract algorithms (Kaya & Yildiz, 2024).

Agreement Between CDM and Traditional Total Scores

Table 4. *Concordance between diagnostic and total-score classifications*

Metric	Result	Interpretation
Simple Agreement	71.2%	Learners received the same broad classification from both methods.
Cohen's Kappa	0.45	Moderate agreement; significantly better than chance but not diagnostically strong.
False Positives	15.0%	Traditional test indicated mastery although CDM identified critical non-mastery.
False Negatives	13.8%	Traditional test indicated non-mastery although CDM showed mastery of most attributes.

Although simple agreement reached 71.2%, Cohen's Kappa was only 0.45, indicating moderate agreement after chance agreement was considered. The two approaches disagreed for 28.8% of learners: 15.0% were false positives under the traditional test, and 13.8% were false negatives. A learner could therefore appear generally successful while still lacking a critical attribute such as regrouping, or appear unsuccessful because of a small number of highly weighted items despite mastery of most foundations.

The discrepancy confirms the diagnostic limitation of total scores. Broad classification cannot show whether learners need place-value instruction, basic-fact remediation, procedural support, or only increased fluency. Wray and Reynolds (2025) similarly questioned the subskill specificity of conventional mathematics assessment. CDM adds instructional value because it makes the reason for failure visible and supports a direct match between assessment evidence and remediation.

Integrated Interpretation of the Findings

Table 5. *Summary of decisions and instructional implications*

Hypothesis	Null Statement	Decision	Evidence
1	Attribute non-mastery differs substantially.	Rejected	Regrouping and place value were the leading deficits.
2	No distinct mastery profiles exist.	Rejected	Three major interpretable profiles were identified.

3	No prerequisite relationships exist.	Rejected in part	A2 -> A4 and A5 -> A6 were significant.
4	CDM and total-score classifications fully align.	Rejected	Kappa = 0.45; 28.8% were misclassified.

Taken together, the findings identify place value and regrouping as the central bottleneck in the numeracy development of the participants. However, the latent profiles show that the severity and breadth of this bottleneck differed across learners. CDM therefore provides two levels of information: the district-level prevalence of each deficit and the learner-level combination of mastered and non-mastered attributes. Both are needed for efficient allocation of intervention time and materials.

The results also demonstrate that remediation should begin with prerequisite understanding, proceed through concrete and representational modeling, and only then emphasize procedural fluency. Repetition without conceptual repair is unlikely to resolve the problem. Direct instruction, guided examples, and practice targeted to the identified attribute can reduce unnecessary cognitive load and support durable schema construction (Adams & Maki, 2023; Hardy, 2025).

CONCLUSION

The study concludes that non-numeracy among the Key Stage 2 learners was not adequately represented by a single total score. The most pervasive weaknesses occurred in addition and subtraction with regrouping, and these difficulties were strongly connected to non-mastery of place value and simple subtraction. Latent Class Analysis showed that learners had distinctly different profiles: some had global foundational deficits, some possessed basic facts but lacked advanced procedures, and others had an isolated regrouping barrier.

The significant prerequisite relationships confirmed that effective intervention must follow the cognitive hierarchy of mathematics skills. Place value should be secured before addition with regrouping, and simple subtraction should be mastered before subtraction with regrouping. The moderate agreement and substantial misclassification between CDM and traditional assessments further demonstrate that total-score testing is diagnostically insufficient. The principal contribution of the study is an evidence-based basis for precision remediation that identifies what each learner needs and the order in which it should be taught.

Recommendation

Schools should supplement traditional numeracy screening with an attribute-based diagnostic assessment for learners who continue to struggle. Mathematics teachers and intervention coordinators should be trained to develop and interpret Q-matrices, review mastery profiles, and use the results to form flexible intervention groups. Instruction should begin with place-value concepts using manipulatives and visual models, followed by explicit bridging to carrying and borrowing procedures. Learners with global deficits should receive intensive foundational instruction, while those with narrow regrouping barriers should receive focused conceptual and procedural practice.

District and school administrators should provide protected intervention time, suitable concrete and visual materials, and regular progress monitoring based on attribute mastery rather than only total scores. Future research should validate the Q-matrix across independent expert panels, replicate the model in other districts, and use longitudinal or experimental designs to determine whether CDM-guided remediation produces sustained gains in numeracy and mathematics confidence.

Table 6. *Proposed precision numeracy remediation framework*

Component	Core Action	Responsible Persons	Expected Indicator
Diagnostic Mapping	Administer an attribute-linked numeracy assessment and generate CDM profiles.	Math teachers, testing coordinator	Individual mastery map
Foundational Repair	Teach A1-A3 and A5 through manipulatives, visual models, and explicit practice.	Classroom and intervention teachers	Mastery of missing basic attributes

Place Value to Regrouping	Secure A2 before A4; connect exchanges to concrete base-ten representations.	Math teachers	Improved addition with regrouping
Subtraction Sequence	Secure A5 before A6 through worked examples and guided borrowing practice.	Math teachers	Improved subtraction with regrouping
Profile-Based Grouping	Group learners by Global Deficit, Basic Facts Master, or Regrouping Barrier profiles.	School intervention team	Differentiated intervention plans
Progress Monitoring	Reassess attributes every 4-6 weeks and regroup learners based on mastery change.	School head, math coordinator	Documented mastery progression

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