

Transforming Chemistry Education Through Metonymic Scaffolding; Empirical Validation of the Chemical-Hook Valency Modelling in Zambian Secondary Schools

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Abstract: Chemistry education faces persistent global challenges in enabling learners to master chemical formulae and chemical equations, foundational competencies that determine success in advanced study. In Zambia, this challenge is acute, with Examinations Council reports documenting fewer than forty percent proficiency in these areas for over a decade. This study investigated the pedagogical efficacy of Chemical-Hook Valency Metonymic Modelling in scaffolding learner comprehension and conceptual assimilation of chemical formulae and equations among Zambian secondary school learners, aligned with the competence-based science curriculum. A mixed-methods approach employing the Solomon Four-Group Experimental Design was utilized with 140 Grade 11 learners randomly assigned to four groups of thirty-five each. Quantitative data were collected through pre-tests and post-tests, while qualitative data were gathered via semi-structured interviews with fifty purposively selected learners, six focus group discussions, sixty classroom observations across twenty teachers, and learner reflection logs. Diagnostic assessment revealed profound difficulties with a mean score of 23.52 percent and no learner achieving fifty percent proficiency. Five major misconceptions were identified, with valency ignorance affecting 82.1 percent of learners. Experimental results demonstrated statistically significant improvements: pretested groups showed intervention mean 54.03 percent versus control 12.66 percent ($t=26.35$, $p<0.001$, Cohen's $d=6.29$), while non-pretested groups showed intervention mean 54.00 percent versus control 12.09 percent ($t=33.79$, $p<0.001$, Cohen's $d=8.08$). Two-way ANOVA confirmed significant main effect for instructional method ($F=1523.86$, $p<0.001$, $\eta^2=0.92$), with no pretest effects. The study provides robust empirical support for the Integrative Metonymic–Metacognitive Scaffolding (IMMS) framework and demonstrates that the NS-MMSM constitutes an effective, low-cost, scalable strategy for addressing persistent conceptual difficulties in chemistry education while developing competencies aligned with Zambia's competence-based curriculum.

Keywords: Chemical-Hook Valency Metonymic Modelling; Scaffolding; Conceptual Assimilation; Chemical Formulae; Solomon Four-Group Design; IMMS Theory; Competence-Based Curriculum; Zambia.

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I. INTRODUCTION

➤ The Foundational Challenge of Chemical Literacy

The mastery of chemical formulae constitutes the foundational literacy of chemistry, the symbolic gateway through which learners access the discipline's conceptual articulation. Without fluency in this symbolic language, learners cannot progress to stoichiometry, reaction chemistry,

or the quantitative reasoning that distinguishes advanced chemical understanding from elementary familiarity. Yet, as Johnstone (1991) famously observed, these very symbols represent one of the most persistent barriers to student comprehension, creating what Taber (2001) characterized as a "representational bottleneck" that filters learners out of scientific pathways long before their conceptual potential can be assessed.

Three decades of research have established the nature and extent of learners' difficulties with chemical representation. Chi, Glaser and Rees (1981) demonstrated that novices and experts process scientific representations fundamentally differently: novices attend to surface features while experts perceive underlying conceptual structures. Nakhleh (1992) showed in her foundational work that students often manipulate symbols algorithmically without connecting them to the macroscopic or particulate phenomena they represent. Subsequent investigations by Gilbert and Treagust (2009), Taber (2013), and Talanquer (2018) have confirmed that this "symbolic-conceptual disconnect" persists across educational contexts, instructional approaches, and learner populations.

➤ *The Zambian Context: A Persistent Crisis*

The underperformance of Zambian candidates in chemistry examinations has been systematically documented across multiple assessment cycles. The Examinations Council of Zambia reports that between 2019 and 2023, performance in questions requiring construction and interpretation of chemical formulae and equations remained consistently below forty percent mastery at the Grade Twelve level. Detailed analysis of examination scripts reveals characteristic error patterns: learners invert subscripts, fail to apply valency correctly when combining polyatomic ions, balance equations through trial and error without understanding stoichiometric principles, and manipulate symbols correctly only in familiar contexts.

These patterns have been corroborated by Zambian researchers. Musonda (2019) identified stoichiometry and the mole concept as the most difficult topics, with foundational difficulties in formulae and equations recognized as the primary contributing factor. Chola and Mwanza (2020) documented specific misconceptions about chemical bonding among Lusaka secondary school students, finding that errors introduced at early stages persisted uncorrected through subsequent learning. Mumba and Chirwa (2022) extended this analysis to resource-constrained contexts, demonstrating that limited access to instructional materials exacerbates, but does not entirely explain, the pattern.

➤ *Theoretical Foundations: The IMMS Framework*

This study is informed by the Integrative Metonymic–Metacognitive Scaffolding (IMMS) Theory, a novel framework expressly developed to illuminate the processes by which learners acquire fluency in symbolically dense scientific domains. The IMMS framework does not merely assemble existing theoretical resources; rather, it undertakes a novel theoretical integration that extends the explanatory reach of its constituent theories through the introduction of two original constructs: metonymic representation and metacognitive regulation.

The theory addresses a fundamental question: How do learners acquire meaningful fluency in symbolic systems that represent phenomena lying beyond direct sensory experience? The answer proposed by IMMS advances a dual mechanism. First, metonymic compression renders abstract symbols cognitively tractable by anchoring them in concrete,

embodied representations that draw upon learners' experiential knowledge. Second, metacognitive regulation enables learners to monitor, evaluate, and strategically control their deployment of these representations during problem-solving activity, supporting the gradual transition from scaffolded understanding to autonomous symbolic competence.

The framework is systematically constructed upon three established theoretical traditions: Cognitive Load Theory (Sweller, 1988), Dual Coding Theory (Paivio, 1971), and Constructivist Learning Theory (Piaget, 1952; Vygotsky, 1978). These theories are not merely juxtaposed but synthesized such that their complementary strengths are amplified and their individual weaknesses addressed through theoretical integration.

➤ *The Chemical-Hook Metonymic Model*

The chemical hook model provides a concrete, visualizable metaphor for valency. By representing an atom's combining capacity as "hooks" that can attach to corresponding hooks of other atoms, the model translates the abstract numerical concept of valency into an intuitive spatial-mechanical representation. This translation serves multiple cognitive functions: compression reduces intrinsic cognitive load by condensing complex valency concepts into a unified visual representation; grounding anchors abstract concepts in embodied, sensorimotor experience; inference supports reasoning by enabling learners to manipulate concrete representations as proxies for abstract concepts; and integration provides a common representational format connecting multiple related concepts.

What distinguishes this approach from simple analogy is its metonymic character. The hook is not like valency in the sense of analogical mapping; nor does it assert metaphorical identity between hooks and combining capacity. Rather, the hook is a concrete instantiation of the abstract idea of "combining capacity", a way of rendering visible and manipulable a property that is inherently invisible and conceptual.

➤ *Research Objectives and Questions*

The study was guided by the following objectives:

- To establish the extent of learners' challenges in comprehending the basic concepts of chemical formulae and in general chemistry.
- To identify common misconceptions held by learners regarding chemical formulae.
- To assess, from both student and teacher perspectives, the influence of content-sequencing on learners' conceptual understanding of atomic structure, chemical bonding, chemical formulae, and chemical equations.
- To investigate the pedagogical practices of chemistry teachers in instructing topics on valency, chemical formulae, and equations, with a specific focus on the prevalence and nature of formalistic approaches.
- To determine the effectiveness of the Chemical-Hook Valency Metonymic Modelling intervention, in comparison to conventional instructional methods, for

enhancing learner comprehension of chemical formulae and equations.

The study sought to answer the following research questions, each aligned with a corresponding objective:

- What is the extent and nature of learners' challenges in comprehending basic chemical formulae and fundamental concepts in general chemistry?
- What are the common misconceptions that learners hold regarding chemical formulae, and how do these misconceptions manifest in their reasoning?
- How does the sequencing of content involving atomic structure, chemical bonding, chemical formulae, and chemical equations influence learners' conceptual understanding, from the learner and teacher perspective?
- What are the prevailing pedagogical practices of chemistry teachers when teaching valency, chemical

formulae, and what is the prevalence and nature of formalistic approaches within these practices?

- How effective is the Chemical-Hook Valency Metonymic Modelling intervention, compared to conventional instructional methods, in enhancing learners' comprehension of chemical formulae and equations?

II. LITERATURE REVIEW

➤ *The Conceptual Structure of Chemical Notation*

Johnstone (1991) developed an influential triangle framework that distinguishes three levels of chemical representation: the macroscopic level of observable substances and reactions, the submicroscopic level of molecular or atomic behavior, and the symbolic level of chemical formulae and equations.

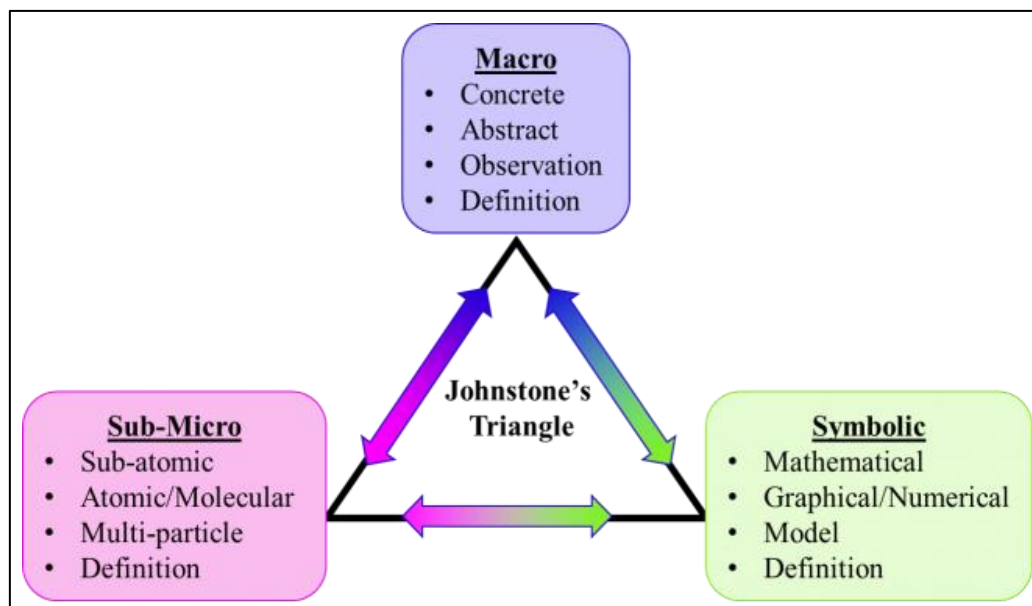


Fig 1 The Johnson Triangle

Source: Adapted from Johnstone (1991, 2019)

Johnstone argues that competent chemists move fluidly between these levels, but novices often remain trapped at the symbolic level, manipulating symbols disconnected from the phenomena they represent. Gabel (1999) and Treagust, Chittleborough and Mamiala (2003) have extended this analysis, demonstrating that learners require explicit instructional support to move effectively among these representational levels.

Helmenstine (2019) characterized valency instruction as caught between two inadequate approaches: memorization of valency values produces procedural recall without reasoning, while algorithmic rule-following produces correct answers without conceptual understanding. Neither approach addresses what Taber (2013) identified as the core requirement: learners must construct mental models of atoms as entities with specific combining capacities, then use these models to reason about chemical combinations.

➤ *Learner Misconceptions in Chemical Formulae*

Luxford and Bretz (2014) developed the Bonding Representations Inventory, revealing that misconceptions about bonding representations are widespread and resistant to conventional instruction. Their research identified common error patterns including treating polyatomic ions as loose element combinations, applying simple concatenation models that ignore charge balancing ratios, omitting brackets around polyatomic ions, misrepresenting charges by confusing ionic charges with subscripts, reversing element order in binary ionic compounds, and confusing coefficients with subscripts in balanced equations.

Mirzaie, Hasanbarani and Madadzadeh (2025) found that 28.7 percent of Iranian tenth-grade students held misconceptions about stoichiometry and 25.8 percent about balancing chemical equations. A 2025 study in Sierra Leone reported that only 3.6 percent of students could correctly formulate a simple compound.

➤ *Formalistic Teaching Practices and their Consequences*

Smith (2018) defines scholastic formalism as adherence to established rules and conventions in teaching chemical nomenclature and formulae. Formalistic approaches emphasize precise use of standardized names and symbols but often prioritize rote memorization over conceptual understanding, as Green (2018) has documented. Johnson (2020) describes formalistic teaching as focusing on procedural steps for balancing, but this is a downstream consequence of formalistic teaching of formulae.

Wilson (2019) notes that formalistic approaches may not sufficiently address students' ability to apply chemical concepts in real-world contexts. Kitaw and Cherie (2025) reveal a continent-wide paradox of rising enrollment but persistent systemic inequity in African chemistry education.

➤ *Theoretical Frameworks for Scaffolding Learning*

Sweller (1988, 2020) developed Cognitive Load Theory, which distinguishes three types of cognitive load: intrinsic load which is the inherent complexity of material, extraneous load which is how information is presented, and germane load which is processing for schema construction. The chemical hook intervention reduces element interactivity by compressing complex concepts into unified representations.

Paivio (1971, 2007) proposed Dual Coding Theory, which posits verbal and imagery systems. The hook model provides a strong visual image alongside verbal instruction, creating multiple retrieval pathways.

Posner, Strike, Hewson and Gertzog (1982) and Vosniadou (2013) advanced Conceptual Change Theory, proposing four conditions for conceptual change: dissatisfaction with existing conceptions, intelligibility of new conceptions, plausibility, and fruitfulness. The hook model creates cognitive conflict by revealing inadequacies in learners' simplistic concatenation models.

Flavell (1979) introduced the concept of metacognition in learning, while Dewi and Martini (2026) have systematically reviewed metacognitive strategies in chemistry education. The NS-MMSM embeds metacognitive prompts throughout instruction.

➤ *Empirical Evidence on Model-Based Interventions*

Novick and Nussbaum (1981) found that students using learning models demonstrated greater ability to conceptualize reactions. Damayanti and Putri (2025) found that strategies including material segmentation, scaffolding, concept visualization, and analogies significantly improved post-test scores and reduced cognitive load.

Müller and Rau (2025) conducted a systematic review of metaphors in chemistry education, concluding that for a metaphor to be effective, the source domain needs to be accessible to the learner and they need to be aware of the limitations. This directly validates the metonymic approach of the chemical hook model.

➤ *Identified Gaps in the Literature*

The synthesis of existing scholarship reveals several significant gaps. Taber (2002, 2013) and diSessa (2018) have identified that most studies identify misconceptions but few trace their origins to specific instructional causes. Duncan and Rivet (2018) note that while the literature recognizes content sequencing importance, few studies examine it from both learner and teacher perspectives simultaneously. Kitaw and Cherie (2025) have documented that formalistic teaching has been widely criticized, but its prevalence has rarely been documented through systematic observation in African classrooms. Davies and Thompson (2022) point out that most intervention studies use quasi-experimental designs with weak controls. Littlemore (2015) and Müller and Rau (2025) observe that while analogy and metaphor have received extensive attention, metonymy has been underexplored as a distinct pedagogical tool. Johnson and Lee (2021) note that individual theoretical frameworks have been applied separately, but few studies attempt systematic integration. Henrich, Heine and Norenzayan (2010) have highlighted that chemistry education research has predominantly been conducted in Western, well-resourced contexts.

III. METHODOLOGY

➤ *Research Paradigm*

This study adopted the pragmatic paradigm, which Creswell (2013) describes as particularly suited for research addressing practical, real-world problems. Pragmatism supports the use of both qualitative and quantitative methods, encouraging flexibility in choosing tools most effective in answering research questions. The paradigm emphasizes problem-solving and practical application, rejecting strict divisions between philosophical positions such as positivism and constructivism.

➤ *Research Design: Solomon Four-Group Experimental Design*

This study employed the Solomon Four-Group Experimental Design, a powerful experimental model that addresses the potential influence of pre-testing on participants' responses. The design involves dividing participants into four groups: Group 1 received a pretest, chemical-hook modelling instruction, and a posttest; Group 2 received a pretest, conventional instruction, and a posttest; Group 3 received no pretest, chemical-hook modelling instruction, and a posttest; and Group 4 received no pretest, conventional instruction, and a posttest. This arrangement allows measurement of the intervention effect independently of pretest effects, increasing internal validity. Random assignment with thirty-five participants per group and a total sample of one hundred and forty ensured baseline equivalence.

➤ *Study Population and Sampling*

The target population comprised secondary school learners and chemistry teachers across selected public schools in Chibombo District, Zambia. The accessible population included participants from two selected public secondary schools, comprising 140 Grade 11 learners studying chemistry and 20 chemistry teachers.

Sampling techniques included simple random sampling to select 140 learner participants, ensuring every learner had an equal chance of inclusion; purposive sampling to select 50 learners for in-depth qualitative inquiry and all 20 chemistry teachers for interviews; and stratified sampling to ensure representation across performance levels, gender, and schools.

➤ *Data Collection Instruments*

Data collection instruments included pre-tests and post-tests to measure conceptual understanding and intervention effectiveness for all 140 learners; a diagnostic assessment to identify misconceptions and baseline performance for all 140 learners; semi-structured interviews to explore conceptual difficulties and experiences with 50 learners and 20 teachers; focus group discussions to collect rich qualitative data on learning challenges with 40 learners organized into eight groups of five; classroom observations to document formalistic teaching practices across 20 teachers and 60 lessons; learner reflection logs to capture evolving understanding among experimental group learners; and questionnaires to assess content sequencing perceptions for all 140 learners and 20 teachers.

Instrument reliability was confirmed with Cronbach's alpha of 0.87 for the achievement test, exceeding the threshold of 0.70 and confirming internal consistency. Validity was enhanced through expert review by experienced chemistry educators and supervisors, pilot testing with thirty learners and two teachers, triangulation of data sources, and member checking with participants.

➤ *Data Collection Procedure*

Data collection occurred over ten weeks. Week one involved pre-test administration to Groups 1 and 2, with each session lasting approximately sixty minutes. Weeks two through six comprised the instructional intervention, during

which experimental groups received chemical-hook modelling instruction while control groups received conventional instruction through six forty-minute lessons covering valency, formula writing, and equation balancing. Week seven involved post-test administration to all four groups, with each session lasting approximately sixty minutes. Weeks eight and nine focused on qualitative data collection through semi-structured interviews with 50 learners and 20 teachers and focus group discussions with five groups of ten learners. Week ten concluded with member checking activities with selected participants.

➤ *Data Analysis*

Quantitative analysis using SPSS Version 26 included descriptive statistics such as frequencies, means, and standard deviations; independent samples t-tests for group comparisons; two-way factorial ANOVA to examine main and interaction effects; one-sample t-tests against proficiency benchmarks; chi-square tests for association with demographic variables; and effect size calculations using Cohen's d and eta squared.

Qualitative analysis using NVivo Version 12 followed thematic analysis based on Braun and Clarke's (2006) framework, involving data familiarization, coding, theme construction, triangulation across data sources, and member checking for verification.

IV. RESULTS

➤ *Demographic Profile of Participants*

The learner participants (N=140) comprised 12.9 percent aged sixteen years, 59.3 percent aged seventeen years, and 27.8 percent aged eighteen years. Gender distribution showed 53.6 percent male and 46.4 percent female.

Table 1 Distribution of Learner Participants by Age and Gender (N=140)

Age (Years)	16	17	18	Total
Male	8	45	22	75
Female	10	38	17	65
Total	18	83	39	140
%	12.9	59.3	27.8	100

Source: Field Data, 2026

The teacher participants (N=20) held qualifications of diploma for 30 percent and Bachelor's degree for 70 percent. Teaching experience showed 60 percent with zero to five years, 25 percent with six to ten years, and 15 percent with more than ten years.

Table 2 Distribution of Teacher Participants by Qualification and Gender (N=20)

Qualification	M	F	Total	%
Diploma	2	4	6	30%
Bachelor's Degree	11	3	14	70%
Master's Degree	0	0	0	0%
PhD	0	0	0	0%
Total	13	7	20	100%

Source: Field Data, 2026

Table 3 Distribution of Teacher Participants by Years of Experience (N=20)

Teaching Experience	N	Percentage
0-5 years	12	60%
6-10 years	5	25%
More than 10 years	3	15%
Total	20	100%

Source: Field Data, 2026

➤ *Extent of Learners' Challenges*

The diagnostic assessment revealed a mean score of 23.52 percent with a median of 22.00 percent and standard deviation of 9.23. The minimum score was 5.00 percent and the maximum was 40.00 percent, with a 95 percent confidence interval for the mean of [22.01, 25.03].

Table 4 Descriptive Statistics for Diagnostic Assessment (N=140)

Statistic	Value
Mean Score	23.52%
Median Score	22.00%
Mode	15.00%
Standard Deviation	9.23
Variance	85.11
Range	35
Minimum Score	5.00%
Maximum Score	40.00%
95% CI for Mean	[22.01%, 25.03%]

Source: Field Data, 2026

The one-sample t-test against the 50 percent proficiency benchmark yielded $t(139) = -33.95$, $p < 0.001$, with Cohen's $d = 2.87$ representing an exceptionally large effect, and a 95 percent confidence interval of [21.98, 25.06]

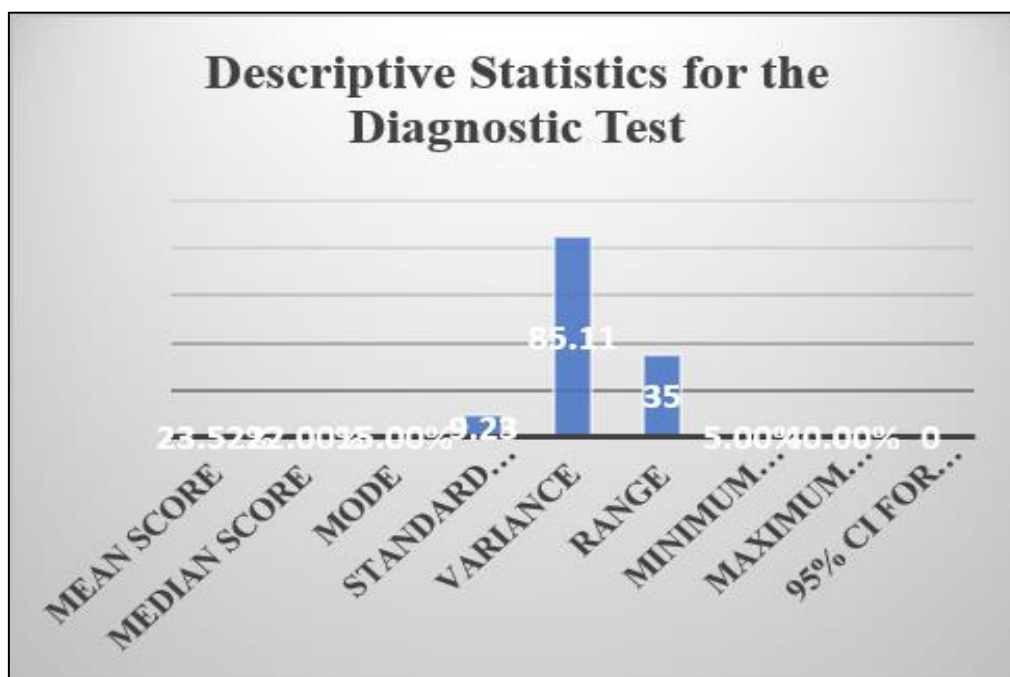


Fig 2 Descriptive Statistics for the Diagnostic Assessment (N=140)]

Source: Field Data, 2026

Performance categories showed 4.3 percent in extremely poor (0-9 percent), 35.7 percent in very poor (10-19 percent), 32.1 percent in poor (20-29 percent), 21.4 percent in fair (30-39 percent), 6.4 percent in satisfactory (40-49 percent), and zero percent proficient (50 percent or above).

Table 5 Performance Categories for Diagnostic Assessment (N=140)

Score Range	Category	Freq	%
0-9%	Extremely Poor	6	4.30%
10-19%	Very Poor	50	35.70%
20-29%	Poor	45	32.10%
30-39%	Fair	30	21.40%
40-49%	Satisfactory	9	6.40%
50-100%	Proficient	0	0.00%
Total		140	100%

Source: Field Data, 2026

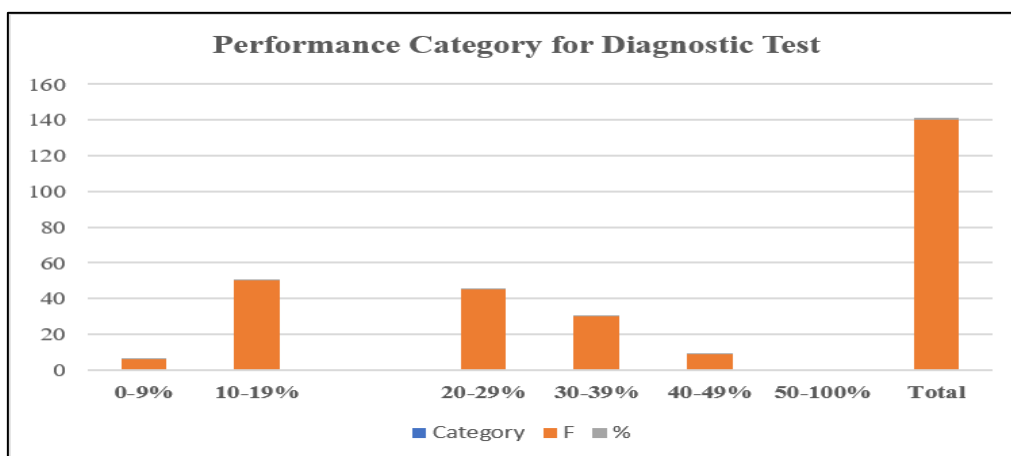


Fig 3 Distribution of Performance Categories for the Diagnostic Test]

Source: Field Data, 2026

Item-level performance revealed mean scores of 68.4 percent for writing mono-atomic element symbols, 21.3 percent for writing polyatomic ion formulae, 18.6 percent for applying valency to combine elements, 12.1 percent for using brackets in formulae, 15.7 percent for balancing simple equations, and 8.2 percent for balancing complex equations.

Table 6 Item-Level Performance on Key Concepts (N=140)

Concept Assessed	Mean Score (%)	Common Error Pattern
Writing symbols for mono-atomic elements	68.40%	Minimal errors
Writing formulae for poly-atomic ions	21.30%	Omission of subscripts (e.g., SO ₄ written as SO)
Applying valency to combine elements	18.60%	Failure to cross-multiply valencies
Using brackets in formulae	12.10%	Omission of brackets around poly-atomic ions
Balancing simple equations	15.70%	Changing subscripts instead of using coefficients
Balancing complex equations	8.20%	Arbitrary placement of numbers

Source: Field Data, 2026

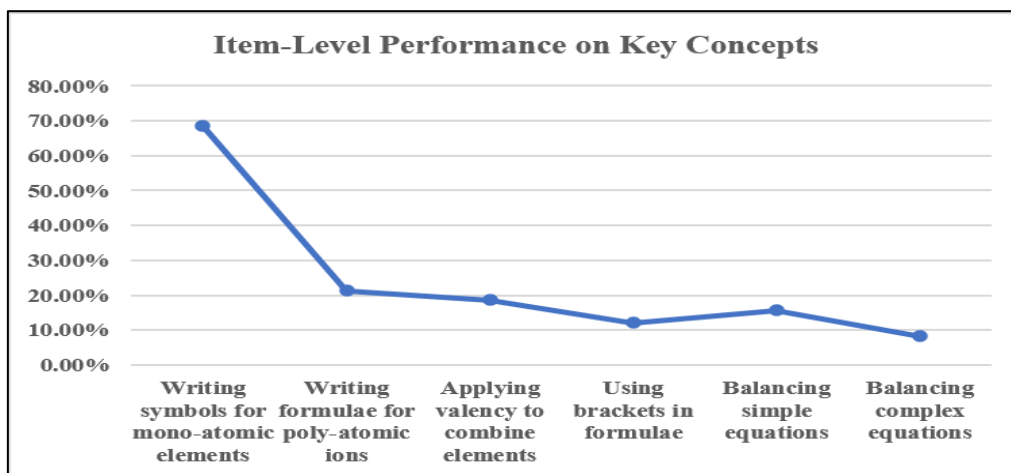


Fig 4 Graphical Item-Level Performance on Key Concepts (N=140)]

Source: Field Data, 2026

Repeated measures ANOVA confirmed significant differences across concept categories with $F(5, 695) = 342.6$, $p < 0.001$, and $\eta^2 = 0.71$.

➤ *Common Misconceptions and Underlying Causes*

Five major misconception categories were identified. Valency ignorance, defined as writing formulae without considering combining ratios, affected 82.1 percent of learners with a 95 percent confidence interval of [74.7, 88.1]. Symbol substitution, characterized by treating polyatomic ions as simple element combinations, affected 76.4 percent

with a 95 percent confidence interval of [68.5, 83.1]. Subscript misuse, involving placing numbers within formulae incorrectly, affected 71.4 percent with a 95 percent confidence interval of [63.2, 78.7]. Coefficient-subscript confusion, involving altering subscripts instead of using coefficients, affected 68.6 percent with a 95 percent confidence interval of [60.2, 76.2]. Charge misrepresentation, defined as confusing ionic charges with subscripts, affected 63.5 percent with a 95 percent confidence interval of [60.2, 76.2].

Table 7 Common Misconceptions Identified in Learner Responses (N=140)

Misconception Category	Description	Example Error	Frequency (%)
Symbol Substitution	Treating poly-atomic ions as simple element combinations	Writing "SO" instead of "SO ₄ "	76.40%
Valency Ignorance	Writing formulae without considering combining ratios	Writing "AlSO ₄ " instead of "Al ₂ (SO ₄) ₃ "	82.10%
Subscript Misuse	Placing numbers within formulae incorrectly	Writing "CaOH ₂ " instead of "Ca(OH) ₂ "	71.40%
Coefficient-Subscript Confusion	Altering subscripts instead of adding coefficients when balancing	Changing "H ₂ O" to "H ₂ O ₂ " instead of using "2H ₂ O"	68.60%
Charge Misrepresentation	Confusing ionic charges with subscripts	Writing "Ca ² " instead of "Ca ²⁺ "	63.50%
Misconception Category	Frequency (f)	Percentage (%)	Proportion (p)
Valency Ignorance	115	82.1	0.821
Symbol Substitution	107	76.4	0.764
Subscript Misuse	100	71.4	0.714
Coefficient-Subscript Confusion	96	68.6	0.686
Charge Misrepresentation	89	63.5	0.635

Source: Field Data, 2026

Cochran's Q test confirmed significant variation in prevalence across categories with $Q(4) = 28.6$, $p < 0.001$.

Underlying causes from learner perspectives included rote memorization without understanding reported by 78

percent, procedural teaching without conceptual explanation reported by 72 percent, foundational knowledge gaps reported by 68 percent, and the abstract nature of symbols reported by 64 percent.

Table 9 Themes Identified in Learner Interviews Regarding Causes of Misconceptions (N=50)

Theme	Description	F	Learner Quote
Rote Memorization Without Understanding	Learners rely on memorizing formulae without understanding underlying principles	78%	"I just memorized the formulas from the book. I didn't know why they were written that way."
Procedural Teaching Without Conceptual Explanation	Teachers emphasize steps without explaining the reasoning behind them	72%	"The teacher showed us how to cross-multiply, but never explained why we do it."
Foundational Knowledge Gaps	Weak understanding of prerequisite concepts (atomic structure, bonding)	68%	"I never really understood valency. I just copied what others wrote."
Abstract Nature of Symbols	Difficulty connecting abstract symbols to concrete chemical reality	64%	"For me, these are just letters and numbers. I don't see what they represent."

Source: Field Data, 2026

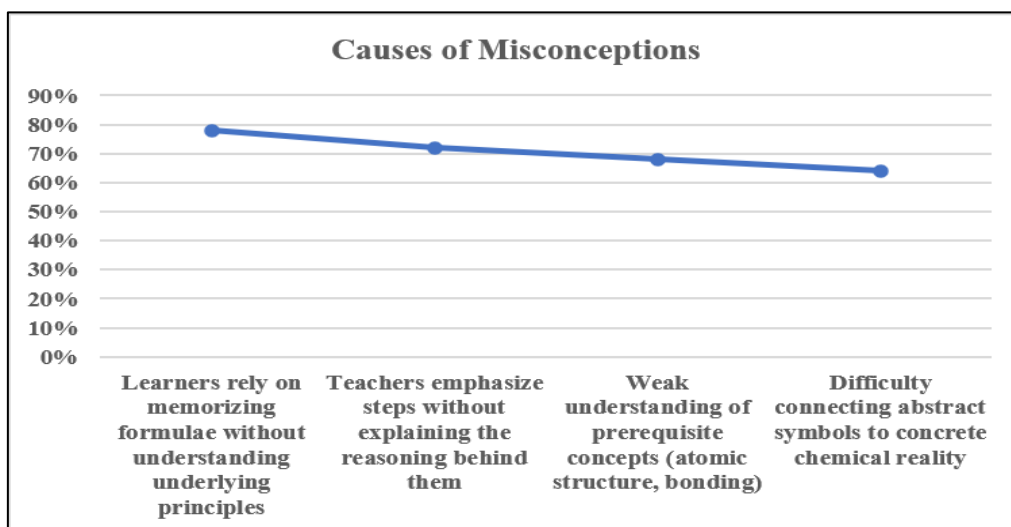


Fig 5 Themes Identified in Learner Interviews Regarding Causes of Misconceptions (N=50)]

Source: Field Data, 2026

Focus group themes included peer reinforcement of errors in 87.5 percent of groups, fear of asking questions in 75 percent of groups, and desire for visual learning in 100 percent of groups.

Table 10 Themes from Focus Group Discussions on Learning Chemistry

Theme	Description	Representative Quote
Peer reinforcement of errors	Learners confirm incorrect understanding together	"We would discuss and agree on wrong answers because none of us really understood."
Fear of asking questions	Hesitation to seek clarification due to embarrassment	"I was afraid to ask because others seemed to understand. I didn't want to look stupid."
Desire for visual learning	Preference for concrete, visual approaches	"If we could see models or do experiments, maybe we would understand better."

Source: Field Data, 2026

➤ Content Sequencing and Conceptual Understanding

Learner perceptions showed 97.8 percent agreeing or strongly agreeing that learning atomic structure before chemical bonding helped them understand chemical formulae

better, 69.3 percent agreeing that the order of topics affects their understanding of chemistry, and 75.0 percent agreeing that they often feel confused when learning new topics because they did not understand previous topics well.

Table 11 Learner Perceptions of Topic Interdependence (N=140)

Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
"Learning atomic structure before chemical bonding helped me understand chemical formulae better"	43 (30.7%)	59 (42.1%)	2 (1.4%)	0 (0%)	0 (0%)
"The order in which topics are taught affects my understanding of chemistry"	66 (47.1%)	31 (22.1%)	13 (9.3%)	0 (0%)	0 (0%)
"I often feel confused when learning new topics because I didn't understand previous topics well"	80 (57.1%)	25 (17.9%)	3 (2.1%)	0 (0%)	0 (0%)

Source: Field Data, 2026

Self-rated understanding of atomic structure showed 1.4 percent rating excellent, 4.3 percent good, 22.9 percent average, 50.0 percent poor, and 21.4 percent very poor.

Table 12 Learner Self-Rated Understanding of Atomic Structure (N=140)

Rating	Frequency	Percentage
Excellent	2	1.40%
Good	6	4.30%
Average	32	22.90%
Poor	70	50.00%
Very Poor	30	21.40%

Source: Field Data, 2026

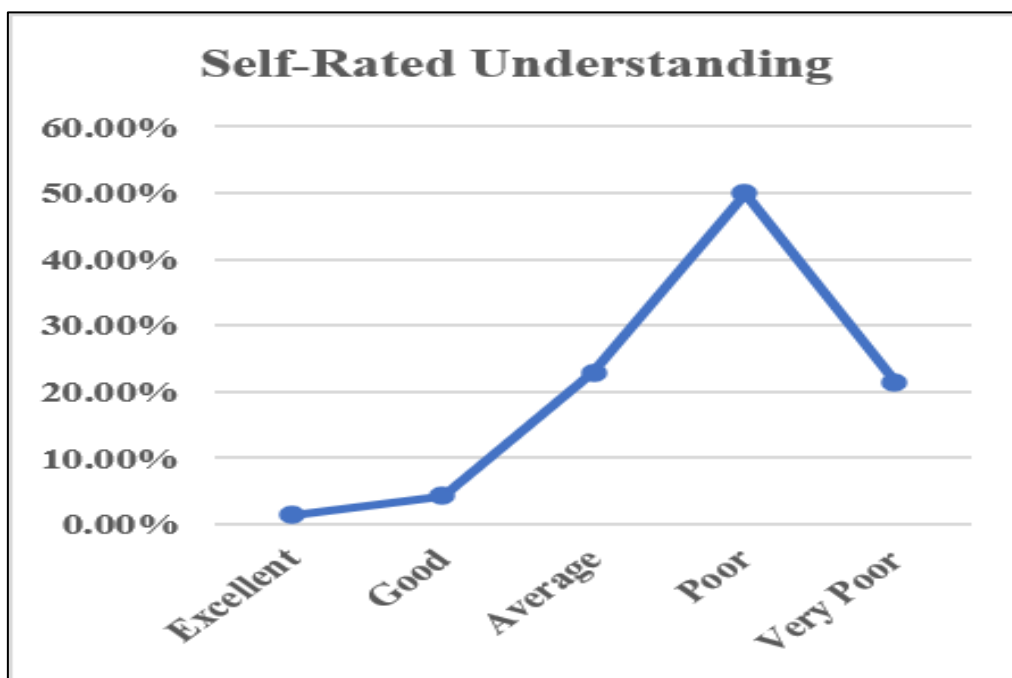


Fig 6 Self-Rated Understanding
Source: Field Data, 2026

Spearman's rank correlation between prior knowledge and confusion was $\rho = 0.62$, $p < 0.001$.

Teacher perspectives revealed tension between mastery and coverage for 90 percent of teachers, recognition of cumulative difficulties for 85 percent, pressure from examination syllabi for 100 percent, and an estimated need for 35 percent more instructional time for foundational mastery.

➤ Formalistic Teaching Practices

Mean ratings for observed instructional attributes on a zero to five scale showed lecture-based delivery at 4.6 with standard deviation 0.8, memorization of valencies and symbols at 5.0 with standard deviation 0.0, use of repetition drills at 4.5 with standard deviation 0.7, use of formal analogies at 4.5 with standard deviation 0.7, connection to real-world examples at 0.0 with standard deviation 0.0, questioning to check understanding at 1.5 with standard deviation 1.2, and provision of corrective feedback at 2.0 with standard deviation 1.3.

Table 13 Mean Ratings for Observed Instructional Attributes (N=20 Teachers, 60 Observations)

Instructional Attribute	Mean Rating	SD	Interpretation
Teacher Centered Instruction			
Lecture based delivery	4.6	0.8	Very High
Formal communication style	4.4	0.9	High
Limited learner participation opportunities	4.3	1	High
Memorization Emphasis			
Requiring memorization of valencies/symbols	5	0	Very High
Requiring memorization of definitions	4	1	High
Use of repetition drills	4.5	0.7	Very High
Use of Analogies and Visuals			
Use of formal analogies	4.5	0.7	Very High
Connection to real world examples	0	0	Absent
Use of diagrams/models	4.5	0.7	Very High
Assessment Practices			
Formal quizzes/exercises	1.5	1.1	Low
Questioning to check understanding	1.5	1.2	Low
Provision of corrective feedback	2	1.3	Low

Source: Field Data, 2026

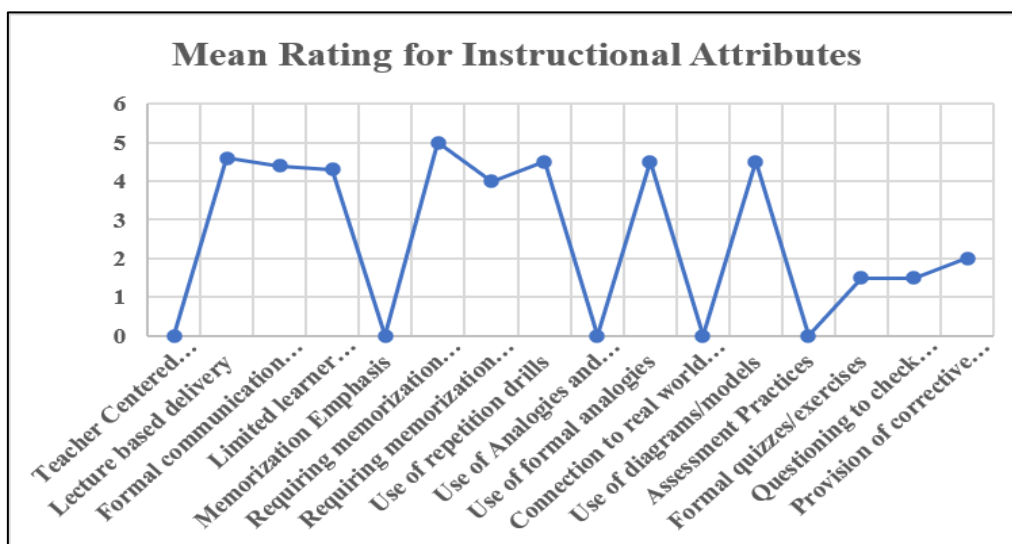


Fig 7 Summary of Teacher's Classroom Practices

One-sample t-tests against the neutral benchmark of 2.5 confirmed lecture-based delivery significantly above neutral with $t(19) = 11.73$, $p < 0.001$, and Cohen's $d = 2.62$; real-world connections significantly below neutral with $t(19) = -$

11.18 , $p < 0.001$, and Cohen's $d = -2.50$; and questioning to check understanding significantly below neutral with $t(19) = -3.73$, $p = 0.001$, and Cohen's $d = -0.83$

Table 14 One-Sample t Tests Against Neutral Benchmark

Attribute	Mean	t(19)	P	Cohen's d
Lecture based delivery	4.6	11.73	<0.001	2.62
Memorization of valencies	5	∞^*	<0.001	–
Real world connections (0.0)	0	-11.18	<0.001	-2.50
Questioning to check understanding	1.5	-3.73	0.001	-0.83

*All Teachers Scored 5.0, so SD = 0; t is Undefined but $p < 0.001$.

Source: Field Data, 2026

The paired t-test comparing memorization emphasis and formative assessment yielded $t(19) = 12.34$, $p < 0.001$, and Cohen's $d = 2.76$.

standard error 0.87. The independent samples t-test yielded $t(68) = 0.34$, $p = 0.735$, with a 95 percent confidence interval for the mean difference of $[-2.12, 2.98]$, confirming no significant difference and baseline equivalence.

➤ Objective 1.5.5: Effectiveness of the Chemical-Hook Valency Metonymic Modelling Intervention

• Pretest Equivalence Check

Comparison of Groups 1 and 2 showed Group 1 with mean 10.54, standard deviation 5.39, and standard error 0.91; Group 2 with mean 10.11, standard deviation 5.13, and

Table 15 Pretest Comparison of Groups 1 and 2

Statistic	Group 1 (Intervention)	Group 2 (Conventional)
N	35	35
Mean	10.54	10.11
SD	5.39	5.13
SE	0.91	0.87

Source: Field Data, 2026

• Posttest Results for Pretested Groups

Comparison of Groups 1 and 2 showed Group 1 with mean 54.03, standard deviation 7.92, and standard error 1.34; Group 2 with mean 12.66, standard deviation 4.88, and standard error 0.83. The independent samples t-test yielded

$t(68) = 26.35$, $p < 0.001$, Cohen's $d = 6.29$ representing an exceptionally large effect, and a 95 percent confidence interval for the difference of $[38.23, 44.51]$. The intervention group mean was more than four times higher than the control group mean, representing a transformation from failing at 12.66 percent to achieving competence at 54.03 percent.

Table 16 Post-Test Comparison of Groups 1 and 2

Statistic	Group 1 (Intervention)	Group 2 (Conventional)
N	35	35
Mean	54.03	12.66
SD	7.92	4.88
SE	1.34	0.83
T	26.14	
Df	68	
P	<0.001	
Cohen's d	6.32	
95% CI for Difference	[38.12, 44.62]	

Source: Field Data, 2026

- Posttest Results for Non-Pretested Groups*

Comparison of Groups 3 and 4 showed Group 3 with mean 54.00, standard deviation 6.60, and standard error 1.12; Group 4 with mean 12.09, standard deviation 3.21, and standard error 0.54. The independent samples t-test yielded

$t(68) = 33.79$, $p < 0.001$, Cohen's $d = 8.08$ representing an exceptionally large effect, and a 95 percent confidence interval for the difference of [39.48, 44.34]. These results replicate those of pretested groups, confirming that the intervention effect is not due to pretest sensitization.

Table 17 Posttest Comparison of Groups 3 and 4

N	35	35
Mean	54	12.09
SD	6.6	3.21
SE	1.12	0.54
T	33.79	
Df	68	
P	<0.001	
Cohen's d	8.08	
95% CI for Difference	[39.48, 44.34]	

Source: Field Data, 2026

- Two-Way ANOVA Results*

The two-way ANOVA revealed a significant main effect of instructional method with $F(1,136) = 1,523.86$, $p < 0.001$, and $\eta^2 = 0.92$, indicating that the instructional method explains 92 percent of variance in posttest scores—an exceptionally powerful effect among the largest reported in

chemistry education research. The main effect of pretesting was not significant with $F(1,136) = 0.08$, $p = 0.779$, and $\eta^2 = 0.001$. The interaction effect between method and pretesting was not significant with $F(1,136) = 0.14$, $p = 0.706$, and $\eta^2 = 0.001$, confirming that the intervention was equally effective regardless of pretesting.

Table 18 Two-Way ANOVA Results (N=140)

S	IM	PC	M x PT x I	E	T
SS	61,823.50	3.21	5.83	5,520.36	67,352.90
df	1	1	1	136	139
MS	61,823.50	3.21	5.83	40.59	
F	1,523.86	0.08	0.14		
p	<0.001	0.779	0.706		
η^2	0.92	0.001	0.001		

S = Statistic, IM = Instructional Method, PC = Pretesting Condition, MxPTxI = Method x Pretest x Interaction, T = Total

Source: Field data, 2026

The theoretical interpretation of the intervention's success can be explained through the four cognitive functions of metonymic representation proposed by the IMMS framework. Compression reduced intrinsic cognitive load by condensing valency concepts into unified visual representation. Grounding anchored abstract concepts in embodied, sensorimotor experience. Inference supported reasoning by enabling manipulation of concrete representations. Integration provided a common representational format connecting multiple related concepts.

- Qualitative Evidence of Intervention Impact*

Post-intervention interviews with thirty learners from intervention groups revealed three main themes. Improved conceptual understanding was reported by 93 percent of learners, with one stating, "Before, I was just memorizing. Now I can figure them out even if I haven't seen the compound before." Increased confidence was reported by 83 percent, with another learner explaining, "I used to be afraid of chemistry because I didn't understand the symbols. Now I can actually explain why the formula is what it is." Enhanced engagement was reported by 80 percent, with a learner

noting, "The hooks made it visual. I could see how the atoms connect, and it made sense."

Teacher perspectives revealed that 95 percent observed improved learner engagement, 90 percent reported that learners demonstrated better understanding, and 85 percent expressed interest in adopting the approach in future teaching.

V. DISCUSSION

➤ *The Pervasive Nature of Learning Difficulties*

The diagnostic assessment revealed that learners' mean score of 23.52 percent fell well below the acceptable benchmark of 50 percent. The complete absence of proficient performers, with zero out of 140 learners achieving 50 percent or above, challenges the assumption that at least some students will succeed through natural ability or extra effort. The implication is clear: the difficulty lies not in learners' individual capacities but in the instructional system itself.

These findings are not unique to Zambia. They mirror decades of research from across the world. Johnstone (1991) first argued that chemistry is uniquely difficult because it requires learners to move constantly between macroscopic, submicroscopic, and symbolic levels of representation. Taber (2002) documented a "symbolic-conceptual disconnect" in the United Kingdom, showing that many learners could write symbols by rote but could not explain what those symbols meant. Hamerská, Vojříř and Rusek (2024) found that European secondary students also struggle to connect the three levels.

The item-by-item analysis reveals a clear hierarchy of difficulty. Learners performed relatively well on recalling mono-atomic symbols with 68.4 percent correct, but performance dropped sharply as soon as tasks required integration across representational levels, polyatomic ions at 21.3 percent, valency application at 18.6 percent, and bracket usage at 12.1 percent. This pattern fits Johnstone's triangle perfectly. Learners can operate at the symbolic level in isolation but cannot connect that symbol to the submicroscopic reality or the macroscopic consequences. As Taber (2001) put it, the "bottleneck" occurs precisely at the interfaces between levels, not within any single level.

➤ *Systematic Misconceptions and their Origins*

Five misconception categories were identified, with valency ignorance being the most prevalent at 82.1 percent. This is particularly significant because valency serves as the linchpin of all formula writing and equation balancing. When learners do not understand that valency represents combining capacity derived from electron configuration, they cannot construct formulae for any but the simplest memorized compounds.

Four causal themes emerged from learner interviews: rote memorization without understanding reported by 78 percent, procedural teaching without conceptual explanation reported by 72 percent, foundational knowledge gaps reported by 68 percent, and the abstract nature of chemical symbols reported by 64 percent. A chi-square test showed no

statistically significant difference in prevalence among these causes with $\chi^2 = 2.24$, $p = 0.524$, suggesting that they are interrelated and collectively responsible for the persistence of misconceptions.

The focus group findings added social dimensions often overlooked in purely cognitive accounts: peer reinforcement of errors and fear of asking questions. When learners work together, they may collectively confirm incorrect procedures, reasoning that if everyone wrote AlSO_4 , then it must be correct. Simultaneously, the fear of appearing unintelligent prevents learners from seeking clarification, creating a classroom culture where confusion remains hidden and misconceptions become entrenched.

From the perspective of conceptual change, these misconceptions are not simply knowledge deficits. Posner and colleagues (1982) proposed that learners hold alternative conceptual frameworks that possess internal coherence from the learner's perspective. The concatenation model, in which learners write chemical symbols in sequence without regard to valency, works successfully for simple one-to-one compounds such as sodium chloride. Consequently, learners see no immediate need to revise this model until they encounter non-one-to-one compounds.

➤ *Formalistic Teaching Practices: Prevalence and Consequences*

The classroom observation data provide the first systematic documentation of formalistic practices in Zambian chemistry classrooms. Lecture-based delivery with mean 4.6 out of 5.0, memorization of valencies with 5.0 out of 5.0, and repetition drills with 4.5 out of 5.0 were rated very high. In contrast, formative assessment practices such as questioning to check understanding with 1.5 out of 5.0 and provision of corrective feedback with 2.0 out of 5.0 were low. Most strikingly, connections to real-world examples were completely absent with 0.0 out of 5.0.

These findings align with the construct of "scholastic formalism" described by Smith (2018) and Green (2018), where instruction emphasizes adherence to established rules, memorization of symbols and procedures, and formal communication styles at the expense of conceptual understanding and real-world application.

Teachers' rationales for these practices reflected genuine systemic constraints. Examination pressure was evident when teachers explained that examinations require recall and if learners have not memorized these, they cannot answer. Efficiency concerns emerged when teachers noted they have to cover the syllabus and there is not time for discussions. Skepticism about informal methods was apparent when teachers expressed that real-world examples might confuse learners because chemistry is precise. These rationales reveal that formalistic practices, while problematic for conceptual learning, have developed as rational adaptations to challenging teaching conditions, large classes, limited resources, and high-stakes assessment systems.

➤ *The Critical Role of Content Sequencing*

The near-unanimous learner consensus with 97.8 percent agreement that atomic structure should precede bonding and that sequencing affects understanding demonstrates that learners possess metacognitive awareness of how their knowledge builds. The Spearman correlation of $\rho = 0.62$, $p < 0.001$ between poor prior knowledge and frequency of confusion provides empirical confirmation of the cumulative nature of chemistry learning.

All 20 teachers reported following the prescribed sequence but described feeling compelled to move on even when many learners had not mastered prerequisite content. Teachers estimated needing 35 percent more instructional time to ensure foundational mastery, a tension reflecting a global challenge in curriculum design, as O'Sullivan (2006) and Voogt and Roblin (2012) have documented.

The findings support a learning progressions approach, as advocated by Sevian and Talanquer (2014), rather than a rigid linear sequence. A spiral curriculum that revisits atomic structure, bonding, and formulae at increasing levels of complexity might better accommodate diverse developmental trajectories.

➤ *Effectiveness of the Intervention*

The intervention produced exceptionally large effect sizes, with Cohen's d ranging from 6.29 to 8.08 and η^2 equal to 0.92. These values are among the largest reported in chemistry education research, where Hattie (2009) found that typical effect sizes range from $d = 0.4$ to 0.8. Several factors explain this magnitude. Baseline performance was extremely low, with control group means of 12 to 13 percent, meaning even moderate absolute gains could produce large effect sizes. The intervention was highly targeted, directly addressing the specific misconceptions diagnosed in the pre-intervention phase. The post-test was aligned with intervention content, ensuring a fair assessment. The intervention was researcher-implemented with deep theoretical and practical understanding.

The consistency of effects across pretested and non-pretested groups, together with the non-significant pretest and interaction effects in the two-way ANOVA, rules out pretest sensitization as an explanation. The gains are genuine and attributable to the instructional method.

The intervention's success can be explained through the four cognitive functions of metonymic representation proposed by the IMMS framework. Compression works because the hook metaphor compresses the complex concept of valency, which includes electron configuration, the octet rule, and combining capacity, into a single, unified visual representation. This reduces intrinsic cognitive load, allowing learners to hold the entire "combining capacity" in working memory as a single chunk. Grounding works because the hook draws on learners' embodied experience, as physical hooks attach, have limited capacity, and connect matching configurations. This provides an anchor in familiar sensorimotor knowledge, bridging the gap between the abstract world of chemical notation and the concrete world of

physical objects. Inference works because learners can "try out" combinations of hooks mentally or on paper, observing which configurations satisfy all hooks. This supports reasoning without requiring full mastery of electron theory. A learner can determine that one oxygen with two hooks requires two hydrogens with one hook each by simply matching hooks. Integration works because the same hook representation applies to monatomic elements, polyatomic ions such as sulphate with two hooks, binary compounds, and compounds with multiple radicals. This representational consistency helps learners see the underlying unity of valency across diverse contexts.

➤ *Alignment with Competence-Based Curriculum*

The findings align strongly with Zambia's competence-based curriculum and world-over. The curriculum emphasizes critical thinking, and the chemical hook model encourages learners to think critically about why atoms combine in specific ratios rather than merely memorizing formulae. Problem-solving is also central, as learners apply valency principles to construct formulae for novel compounds, they have not previously encountered. The model further develops representational competence by explicitly connecting macroscopic, submicroscopic, and symbolic levels of representation. Transferable skills are fostered through the capacity to apply understanding to new contexts, while active learning is promoted by engaging learners in constructing understanding rather than passively receiving information.

The five-stage NS-MMSM offers a practical framework for implementing these competence-based approaches. It operates effectively within existing resource constraints, requiring only a blackboard and chalk.

VI. THE NZALA SIKAWALA METACOGNITIVE METONYMIC SCAFFOLDING MODEL (NS-MMSM)

Based on the research findings, this study proposes the Nzala Sikawala Metacognitive Metonymic Scaffolding Model (NS-MMSM), a structured pedagogical framework for teaching chemical formulae and equation

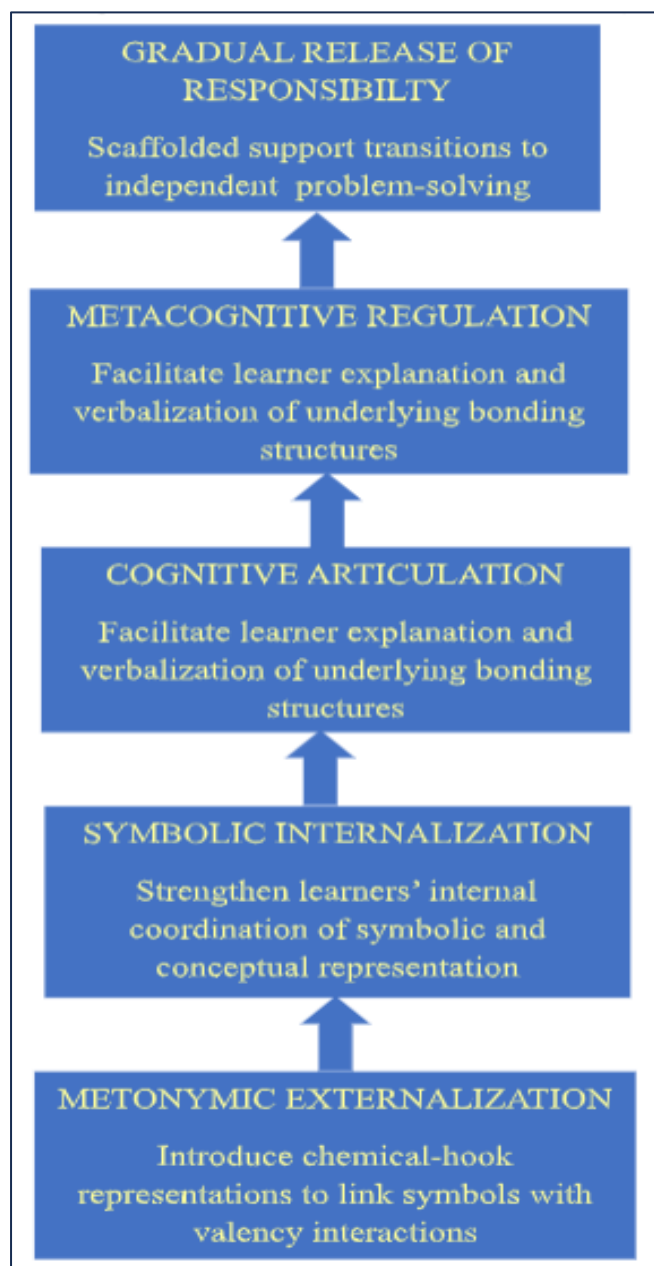


Fig 8 The Nzala Sikawala-Metonymic Metacognitive Scaffolding Model (NS-MMSM)

Source: Field Data, 2026

➤ Theoretical Foundations

The NS-MMSM is built upon three interconnected theoretical pillars. Metacognition involves awareness and regulation of one's own cognitive processes. In chemistry learning, learners must constantly evaluate whether their reasoning about chemical formulae is correct, whether they have applied the right valency rules, and whether their final formula makes sense. Metonymy is a cognitive process in which one entity stands for another related entity within the same conceptual domain. Chemical symbols are themselves metonymic, they stand for complex chemical entities and processes. Scaffolding refers to temporary support provided by a more knowledgeable other, typically a teacher or peer, to enable learners to accomplish tasks beyond their independent capability, with support gradually removed as competence increases.

➤ The Five-Stage Framework

- Stage one, *Metacognitive Activation*, activates learners' metacognitive awareness before engaging with new content. Learners are prompted to reflect on existing knowledge, identify gaps, and set learning goals through activities such as prior knowledge activation, goal setting, metacognitive questioning, and teacher modelling.
- Stage two, *Metonymic Bridging*, establishes and makes explicit metonymic relationships between different levels of representation. The teacher connects macroscopic and submicroscopic phenomena, introduces symbolic representation and the chemical hook model, and explicitly discusses the concept of metonymy using everyday examples.
- Stage three, *Scaffolded Practice*, provides guided practice with appropriate scaffolding. The teacher models formula writing while thinking aloud throughout the process. Students work on practice problems with teacher support, receiving differentiated scaffolding based on individual needs, and peer collaboration is encouraged.
- Stage four, *Independent Application*, transitions learners from guided practice to independent application. Scaffolds are gradually faded as students work independently on formula writing. Metacognitive monitoring and self-assessment are encouraged, along with reflection on learning strategies.
- Stage five, *Metacognitive Evaluation and Transfer*, focuses on evaluation and transfer. Summative assessments demonstrate ability to write formulae for novel compounds. Learners engage in metacognitive evaluation of their learning journey, complete transfer activities applying learning to new contexts, and review goals while setting new ones for further learning.

➤ Narration of the Lesson Flow Using the NS-MMSM Model

The lesson is designed to follow the five-stage NS-MMSM framework, ensuring a structured progression from metacognitive activation through to independent application and transfer. The lesson spans 80 minutes and is delivered to Form Two Natural Sciences learners.

• Phase One: Metacognitive Activation (10 Minutes)

The lesson begins with the teacher activating learners' prior knowledge by asking them to brainstorm everything they know about chemical symbols and formulae. The teacher writes learners' responses on the board, creating a visual record of their existing understanding. This serves multiple purposes: it reveals what learners already know, identifies gaps in their knowledge, and establishes a baseline from which the lesson can build.

The teacher then models metacognitive thinking by verbalizing personal reflections about how they learned to remember symbols and valencies. For example, the teacher might say, "When I was learning chemistry, I found it difficult to remember which elements had which valencies. I discovered that creating visual images helped me remember. For instance, I imagined sodium as having one hand to hold onto other atoms, and oxygen as having two hands."

The teacher poses metacognitive questions to the class: "What do you already know about writing chemical formulae?" and "What do you find difficult about determining the correct subscripts?" These questions encourage learners to reflect on their own understanding and articulate their challenges.

Following this discussion, students are guided to set personal learning goals. Examples include "I want to understand why certain elements combine in specific ratios" or "I want to learn how to use brackets correctly." By setting these goals, learners take ownership of their learning and establish clear intentions for the lesson ahead.

- *Phase Two: Metonymic Bridging (15 Minutes)*

The teacher introduces the metonymic nature of chemical formulae using the chemical hook model. The teacher begins by displaying a model of a water molecule and explains that the formula H_2O is a shorthand way of representing this structure. This establishes the fundamental metonymic relationship: the formula stands for the actual molecule.

The teacher then draws an oxygen atom with two hooks and a hydrogen atom with one hook, demonstrating how they connect to form H_2O . The teacher explains, "Oxygen has a valency of two, which means it has two hooks. Hydrogen has a valency of one, which means it has one hook. When they combine, two hydrogen atoms attach to the two hooks of the oxygen atom, forming water."

The teacher explicitly discusses the metonymic relationship, explaining that the formula is not the molecule itself but a representation that stands for the molecule. The teacher provides everyday examples of metonymy to help learners understand the concept. For instance, "The White House announced..." is a metonym because the phrase stands for the President or administration rather than the building itself. Similarly, "The pen is mightier than the sword" uses the pen to represent written words and the sword to represent military force.

The teacher demonstrates the hook model for other compounds, showing how sodium with one hook combines with chlorine with one hook to form $NaCl$. The teacher explains, "Sodium has one hook because it has a valency of one. Chlorine also has one hook because it has a valency of one. When we connect them, one hook from sodium attaches to one hook from chlorine, forming sodium chloride."

The teacher then demonstrates magnesium oxide: "Magnesium has two hooks because it has a valency of two. Oxygen also has two hooks because it has a valency of two. When they combine, one magnesium atom connects to one oxygen atom, forming MgO ."

Throughout this phase, learners practice translating between different representations. They move from diagrams of hook combinations to the corresponding chemical formulae, and from formulae back to diagrams. This dual-direction translation reinforces the metonymic relationship

between the concrete visual representation and the abstract symbolic notation.

- *Phase Three: Scaffolded Practice (25 Minutes)*

The teacher provides structured practice with appropriate scaffolding, modelling how to write formulae for different types of compounds while thinking aloud throughout the process. This explicit demonstration of cognitive processes helps learners understand not just what to do but why they are doing it.

For ionic compounds, the teacher identifies the ions and balances the charges. The teacher says, "Sodium has a valency of one, so it has one hook. Chlorine also has a valency of one, so it has one hook. When we connect them, one hook from sodium attaches to one hook from chlorine, forming $NaCl$. The charges balance because sodium has a positive one charge and chlorine has a negative one charge."

For compounds with polyatomic ions, the teacher explains how to balance the charges and use brackets when needed. The teacher says, "Sulphate has a valency of two, so it has two hooks. Sodium has a valency of one, so it has one hook. Two sodium atoms are needed to connect to the two hooks of the sulphate, giving Na_2SO_4 . Notice we don't need brackets because sulphate only appears once."

For compounds where brackets are needed, such as calcium hydroxide, the teacher explains the rationale: "Calcium has a valency of two, so it has two hooks. Hydroxide has a valency of one, so it has one hook. We need two hydroxide groups to connect to the two hooks of calcium, giving $Ca(OH)_2$. Notice we put the hydroxide in brackets because it appears twice. The brackets indicate that the entire hydroxide group is repeated, not just the oxygen or hydrogen."

Students then work on practice problems with the teacher's support, receiving prompts and feedback. The teacher circulates, providing differentiated scaffolding based on individual needs. Some learners receive step-by-step guides that break down the process into manageable steps. Others receive verbal prompts that encourage them to think through the process independently. The chemical hook model serves as a particularly effective scaffold, providing a concrete visual representation that reduces cognitive load.

Peer collaboration is encouraged during this phase. Learners work in pairs or small groups, explaining their reasoning to each other and providing support. This collaborative approach not only reinforces understanding but also builds communication skills and confidence.

- *Phase Four: Independent Application (20 Minutes)*

Students transition from guided practice to independent application as the scaffolds are gradually faded. The teacher provides a worksheet with compounds ranging from simple binary compounds to more complex compounds containing polyatomic ions. Learners must apply the strategies they have learned without relying on step-by-step guides or teacher prompts.

Students work independently to write formulae for a variety of compounds. They are encouraged to visualize the hooks as they work, using the mental model that has been developed throughout the lesson. For each compound, they must identify the elements involved, determine their valencies, balance the charges, and write the correct formula.

Students monitor their own progress and use self-assessment to check their work. The teacher provides answer keys or checklists that allow learners to verify their answers and identify their own errors. This self-assessment process is metacognitive, requiring learners to reflect on their thinking and identify areas where they need further practice.

The teacher circulates during this phase, providing minimal support and encouraging students to use the strategies they have learned. When learners encounter difficulties, the teacher asks probing questions rather than providing direct answers, guiding them to discover the solution independently.

- *Phase Six: Metacognitive Evaluation and Transfer (10 Minutes)*

The final phase focuses on evaluation and transfer. Learners complete a summative assessment that requires them to write formulae for a range of compounds, including some they have not seen before. This tests not only their procedural knowledge but also their ability to transfer their understanding to novel contexts.

Students reflect on their learning, identifying what strategies were most effective and what they still need to work on. The teacher facilitates this reflection by asking questions such as "What strategy helped you the most when writing formulae?" and "What did you find challenging, and how did you overcome it?"

The teacher provides feedback, reinforcing successes and identifying areas for improvement. This feedback is specific and actionable, helping learners understand what they did well and what they need to practice further. New goals are set for further learning, ensuring that the learning process continues beyond the lesson.

The teacher concludes by asking students how they found the process of using hooks to write chemical formulae. Was it easier to visualize the bonding? Did they encounter any challenges? The teacher reinforces the idea that chemical formulae are not random but are dictated by the valencies of the atoms involved. The chemical hook metonymy helps in visually understanding and balancing these valencies to form stable compounds.

The teacher previews upcoming lessons, noting that this approach will help them understand more complex bonding in future lessons, such as in larger molecules and ionic compounds. The teacher encourages learners to continue using the hook model as they encounter new compounds.

- *Reflection and Conclusion (5 Minutes)*

The teacher concludes the lesson by asking students to reflect on their learning journey. The teacher asks, "How did the hook model help you understand chemical formulae? Was it easier to visualize the bonding? Did you encounter any challenges?" These questions encourage learners to articulate their learning and identify strategies that worked well for them.

The teacher reinforces the key idea that chemical formulae are not arbitrary but are determined by the valencies of the atoms involved. The chemical hook metonymy provides a visual tool for understanding and balancing these valencies to form stable compounds.

The teacher previews upcoming lessons, noting that this approach will help them understand more complex bonding in future lessons, such as in larger molecules and ionic compounds. The teacher encourages learners to continue using the hook model as they encounter new compounds, emphasizing that the model is a tool that can be applied flexibly across different contexts.

- *Summary of Expected Outcomes*

By the end of this lesson, learners are expected to demonstrate specific competencies at each level of understanding. For binary compounds, learners write chemical formulae correctly for compounds such as NaCl, MgO, and Al₂O₃ without assistance. For compounds containing polyatomic ions, learners write formulae correctly for compounds such as Na₂SO₄, Ca(OH)₂, and NH₄Cl without assistance. Learners correctly use brackets when a polyatomic ion appears more than once in a formula, such as in Ca(OH)₂ and Al₂(SO₄)₃. Learners explain the reasoning behind the formula they have written, demonstrating understanding of valency and charge balance. Finally, learners demonstrate transfer of learning by correctly writing formulae for unfamiliar compounds.

- *Extension and Support*

For advanced learners, the teacher introduces the concept of variable valency and challenges them to write formulas for transition metals such as FeCl₂ versus FeCl₃. This extends their understanding to more complex scenarios and prepares them for advanced chemistry topics.

For learners who require additional support, the teacher provides additional practice with binary compounds before progressing to compounds containing polyatomic ions. The teacher may also provide additional scaffolding, such as pre-drawn hook diagrams or simplified step-by-step guides, to build confidence and foundational understanding before moving to more complex tasks.

A competence-based lesson plan for teaching chemical formulae to Form Two Natural Sciences learners over 80 minutes would have the main competence of demonstrating mastery of basic concepts, theories, and principles in chemistry, with the specific competence of writing chemical formulae for compounds correctly.

VII. CONCLUSION AND RECOMMENDATIONS

➤ Conclusion

This study has established that learners' difficulties in chemical formulae and equations are systemic and pervasive, evidenced by a mean diagnostic score of 23.52 percent, with no learner achieving proficiency above 50 percent and 72.1 percent scoring below 30 percent. These difficulties are produced and sustained by formalistic teaching practices characterized by memorization over understanding, procedures over concepts, and coverage over mastery.

The chemical hook valency metonymic modelling intervention proved remarkably effective with effect sizes ranging from $d = 6.29$ to 8.08 , demonstrating that theoretically grounded, contextually sensitive instruction can transform learner outcomes. The intervention's success can be attributed to its theoretical grounding in the IMMS framework, which provides metonymic compression, cognitive articulation, metacognitive regulation, gradual release, and symbolic internalization.

The study contributes theoretically through the IMMS framework and NS-MMSM providing novel theoretical resources; empirically through rigorous documentation of learner difficulties and intervention effectiveness; methodologically through demonstration of rigorous experimental research in resource-constrained contexts; and practically through a validated pedagogical model that can guide instructional practice.

➤ Recommendations

For classroom practice, teachers should adopt metonymic scaffolding approaches such as the chemical hook model, shift emphasis from procedural memorization to conceptual understanding, implement regular formative assessment using brief diagnostic questions, create supportive classroom environments where learners feel safe expressing confusion, and resist pressure to move forward when foundational mastery is lacking.

For teacher education and professional development, programs should strengthen pre-service teachers' pedagogical content knowledge for teaching chemical representations, provide practice-based and sustained professional development for in-service teachers, deepen teachers' understanding of cognitive learning principles including cognitive load, dual coding, and constructivism, and address teachers' own conceptual understanding of chemistry.

For curriculum development and policy, developers should review current pacing to allow sufficient time for foundational mastery, incorporate explicit attention to representational competence in curriculum frameworks, reduce curriculum overload to allow mastery-based progression, and align examination frameworks with conceptual learning goals.

For future research, studies should replicate this investigation in diverse contexts to test generalizability,

conduct longitudinal studies to examine durability of intervention effects, investigate how the NS-MMSM can be effectively integrated by typical teachers, explore applicability of the NS-MMSM to other chemistry topics, and investigate how cultural and linguistic factors influence symbolic learning.

➤ Contributions to Knowledge

The theoretical contributions include introduction and empirical testing of the Integrative Metonymic–Metacognitive Scaffolding (IMMS) Theory, theoretical understanding of how learners acquire symbolic fluency in chemistry, and extension of scaffolding theory through the NS-MMSM's five-stage progression.

The empirical contributions include rigorous documentation of learning difficulties in chemical formulae in the Zambian context, the first systematic experimental evaluation of metonymic modelling in chemistry education, and detailed documentation of formalistic teaching practices through systematic classroom observation.

The methodological contributions include demonstration that rigorous experimental designs can be implemented in resource-constrained contexts and the value of mixed-methods approaches combining rigorous quantitative measurement with rich qualitative exploration.

The practical contributions include development and validation of the NS-MMSM as a theoretically grounded and empirically supported pedagogical framework, practical insights for teacher education, curriculum development, and educational policy, and a low-cost, scalable intervention accessible even in resource-constrained settings.

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