



Epistemic Agency as a Mediator in Dual-Path Learning: Insights from Indonesian Chemistry Classrooms

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Article Info

Article history:

Received: 09-09-2025

Revised: 03-12-2025

Accepted: 21-01-2026

Available online: 01-02-2026

Keywords:

Epistemic Agency;
Constructivist Learning
Environment; Rasch Analysis;
Conceptual Understanding;
Science Education

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Abstract

This study investigates the mediating role of epistemic agency in the relationship between students' perceptions of constructivist learning environments and their conceptual understanding in Indonesian chemistry classrooms. A sequential explanatory mixed-methods design was employed, integrating quantitative and qualitative approaches. In the quantitative phase, data were collected from 712 high school students across five schools using an adapted Constructivist Learning Environment Survey (CLES) and a three-tier diagnostic chemistry test. Rasch modeling confirmed the strong psychometric properties of the adapted CLES, while structural equation modeling (SEM) revealed that epistemic agency significantly mediated the relationship between classroom environment perceptions and conceptual understanding. In the qualitative phase, thematic analysis of interviews with 12 selected students uncovered three dominant themes contributing to misconceptions: limited dialogic space, lack of contextualization, and teacher-dominated instruction. The integration of both data strands demonstrates that epistemic agency is not only influenced by pedagogical practices but also shaped by cultural norms. These findings extend the dual-path learning framework by embedding agency as a key mechanism for conceptual change. Pedagogically, the results underscore the need for dialogic, student-centered learning environments that promote active participation and reduce misconceptions. Policy-wise, the findings align with the OECD Learning Compass 2030 and Indonesia's Merdeka Belajar curriculum, emphasizing the importance of agency-oriented strategies in achieving global education standards.

How to Cite: Abas, R. N. R., Musa, W. J. A., Laliyo, L. A. R., Pikoli, M., & La Kilo, A. (2026). Epistemic Agency as a Mediator in Dual-Path Learning: Insights from Indonesian Chemistry Classrooms. *Jambura Journal of Educational Chemistry*, 8(1), 77-83. <https://doi.org/10.37905/jjec.v8i1.34366>

1. INTRODUCTION

Over the past two decades, science education has experienced a profound paradigm shift, moving from content-driven instruction toward constructivist pedagogy that prioritizes student agency, collaborative meaning-making, and contextualized learning experiences. This transformation resonates strongly with the OECD Future of Education and Skills 2030 framework, which emphasizes critical thinking, epistemic awareness, and active participation in knowledge construction (OECD, 2019).

Within this discourse, the Constructivist Learning Environment Survey (CLES) has been widely applied to measure students' perceptions of classroom environments across diverse cultural settings (P. C. Taylor et al., 1997; S. P. Taylor, 2023; Triantafyllou,

2012). Nevertheless, psychometric validation of this instrument in Southeast Asian contexts remains limited. Furthermore, existing studies predominantly rely on classical test theory, with only a few employing modern psychometric approaches such as Rasch analysis, which offers a more robust examination of item functioning and construct validity (Boone et al., 2014; Boone & Staver, 2020).

Recent research has increasingly underscored the role of epistemic agency—students' capacity to articulate critical perspectives and engage with the uncertainty of scientific knowledge—in shaping conceptual understanding (Cook & Warwick, 2023; Kirk, 2025; Schaefer et al., 2024). While Western studies have demonstrated that dialogic, student-centered learning environments promote deeper conceptual change,

evidence from Asian educational systems, where classroom dialogue is often culturally constrained, remains scarce (Mohammed & Kinyó, 2022).

Simultaneously, persistent misconceptions in chemistry, particularly in abstract topics such as chemical bonding, ionization, and acid-base reactions, continue to challenge educators. These misconceptions frequently arise when instruction lacks contextualization and dialogic engagement (Moreira & Talanquer, 2023; Wandersee et al., 1994). Three-tier diagnostic assessments, which integrate multiple reasoning layers, have proven effective in detecting such misconceptions (Gurel et al., 2015; Jusniar et al., 2020; Setiawan & Ilahi, 2022). However, limited research has combined diagnostic approaches with students' perceptions of learning environments to explain conceptual mastery.

Grounded in the dual-path learning framework, which emphasizes that affective and cognitive dimensions jointly drive conceptual change in science education (González-Howard & McNeill, 2020; Zembylas, 2005), this study incorporates epistemic agency as a mediating construct to bridge these theoretical and practical gaps. By embedding epistemic agency within constructivist learning models, the research underscores the transformative potential of student engagement in scientific discourse, a process essential for fostering critical thinking and improving comprehension (Hoang et al., 2023; Odden et al., 2022). To empirically investigate these relationships, Rasch-validated measures of students' perceptions were combined with a three-tier diagnostic test, enabling an analysis of how classroom dimensions—particularly critical voice and personal relevance—predict conceptual understanding in Indonesian chemistry classes (Facca et al., 2020; Yu et al., 2024). These findings align with contemporary evidence that active student involvement enhances the retention and application of knowledge while promoting collaborative inquiry (Revill, 2020; Tan et al., 2021). Furthermore, by contributing to cross-cultural psychometric validation, this study extends theoretical perspectives on how dialogic, student-centered environments foster deeper engagement with scientific content and improve learning outcomes across diverse educational contexts (Yang et al., 2024).

2. METHOD

2.1 Research design

This study adopted a sequential explanatory mixed-methods design, combining quantitative and qualitative phases to provide a comprehensive understanding of the investigated phenomenon. In the first phase, a cross-sectional correlational approach was applied to examine the relationships between students' perceptions of constructivist learning environments (independent variable) and their conceptual understanding in chemistry (dependent variable). This phase yielded statistical evidence to guide the subsequent qualitative exploration.

The second phase employed an in-depth qualitative approach through semi-structured interviews aimed at uncovering underlying misconceptions and contextual factors influencing learning. The qualitative analysis enriched the statistical findings, offering a nuanced interpretation of the relationships observed. This methodological integration ensured both breadth and depth in addressing the research questions (Creswell & Plano Clark, 2018).

The adoption of this design was justified by two considerations. First, mixed methods allowed for the integration of statistical rigor with narrative exploration, producing a more holistic understanding of the learning process. Second, the cross-sectional nature of the quantitative phase captured relationships at a single point in time, although causal interpretations remain limited. Future research is recommended to employ longitudinal designs to strengthen causal inferences.

2.2 Population and Sampling

Participants consisted of 712 high school students from five schools in Gorontalo Province, Indonesia, selected through purposive sampling to ensure variability in geographic location and school status (public/private). For the qualitative phase, 12 students were purposively chosen using a maximum variation strategy, ensuring representation across low-perception and high-misconception profiles.

2.3 Research Instruments

Two primary instruments were employed. The first was a locally adapted version of the Constructivist Learning Environment Survey (CLES), originally developed by Johnson & McClure, (2004). It measures five subscales—Personal Relevance, Critical Voice, Shared Control, Student Negotiation, and Uncertainty of

Science—capturing students' perceptions of constructivist classroom features. The adaptation process followed ITC guidelines, including forward–back translation and expert validation to ensure cultural relevance. Items were rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree).

The second instrument was a three-tier diagnostic chemistry test comprising 15 items across core topics (atomic structure, chemical bonding, redox reactions, and stoichiometry). Each item assessed: (1) conceptual response, (2) reasoning, and (3) confidence level. Scoring followed Treagust (2006) and Habiddin & Page (2019) classification: 2 for correct concept and reasoning with high confidence, 1 for partial understanding or low confidence, and 0 for misconceptions. This structure allowed for a deeper diagnosis of misconceptions beyond surface-level correctness.

2.4 Data Analysis and Validity

Quantitative data were analyzed using Rasch modeling with Winsteps 4.5.5 to validate the construct of the adapted CLES. Analyses included item fit (INFIT/OUTFIT MNSQ within 0.7–1.3), unidimensionality, and reliability indices (>0.80 for both item and person) (Linacre, 2020). Differential Item Functioning (DIF) tests examined potential bias across gender and school type. Rasch modeling was chosen for its strength in providing interval-level measurement and detecting item bias compared to classical test theory (Bond & Fox, 2015).

Subsequently, Spearman correlations were calculated to assess associations between learning environment dimensions and conceptual understanding, followed by Structural Equation Modeling (SEM) with bootstrapping to test the mediating role of epistemic agency. SEM was appropriate for examining latent constructs and mediating effects that simple correlations could not fully capture (Kline, 2023).

For the qualitative phase, interview data were analyzed thematically using NVivo. The analysis followed Braun and Clarke (2006) six-phase approach—familiarization, coding, theme generation, review, definition, and reporting—guided by the theoretical constructs of epistemic agency and dual-path learning. This process ensured that themes were both data-driven and theory-informed.

2.5 Credibility and Reliability Measures

To enhance validity, quantitative analyses adhered to Rasch reliability thresholds, while qualitative

data credibility was ensured through member checking, intercoder reliability, and source triangulation. The integration of both data strands in the final interpretation phase allowed for robust conclusions regarding the relationships under investigation.

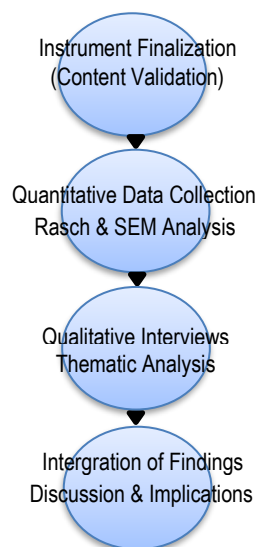


Figure 1. Research flowchart: sequential explanatory mixed methods

3. RESULT AND DISCUSSION

3.1. Result

Rasch Model Analysis

Rasch analysis confirmed the strong psychometric properties of the adapted Constructivist Learning Environment Survey (CLES). Item reliability reached 0.92, while person reliability was 0.87, both exceeding the recommended threshold of 0.80 (Bond & Fox, 2015; Laliyo et al., 2024). All items exhibited INFIT/OUTFIT MNSQ values within the acceptable range (0.72–1.25), indicating a good fit to the Rasch model. Principal Component Analysis (PCA) of residuals supported unidimensionality, with 39% variance explained by the primary construct (Liu & Boone, 2023).

Differential Item Functioning (DIF) analysis revealed significant differences in the Critical Voice dimension, with $\Delta\beta = 0.45$ ($p < 0.05$) between male and female students. This finding suggests potential gender-related differences in expressing critical perspectives, highlighting the importance of considering cultural and social dynamics in interpreting perceptions of learning environments.

Correlations and Mediation Modeling

Spearman correlation analysis demonstrated that Critical Voice and Personal Relevance were the strongest predictors of students' conceptual understanding, consistent with findings from prior research that emphasizes the role of student voice in fostering deeper learning (Eriksson & Lindberg, 2016). In contrast, Uncertainty of Science exhibited the weakest association.

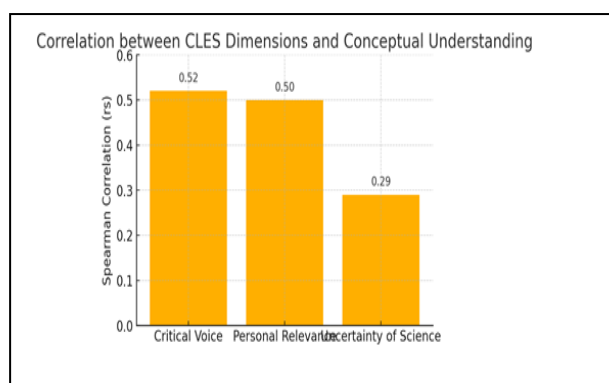


Figure 2. Spearman correlation between CLES dimensions (critical voice, personal relevance, and uncertainty of science) and students' conceptual understanding.

Structural Equation Modeling (SEM) further revealed that epistemic agency functioned as a significant mediator between perceptions of the learning environment and conceptual understanding, with a mediation coefficient of $\beta = 0.31$ ($p < 0.001$). Model fit indices indicated excellent fit ($\chi^2/df = 1.90$; RMSEA = 0.045; CFI = 0.95), supporting the robustness of the proposed model.

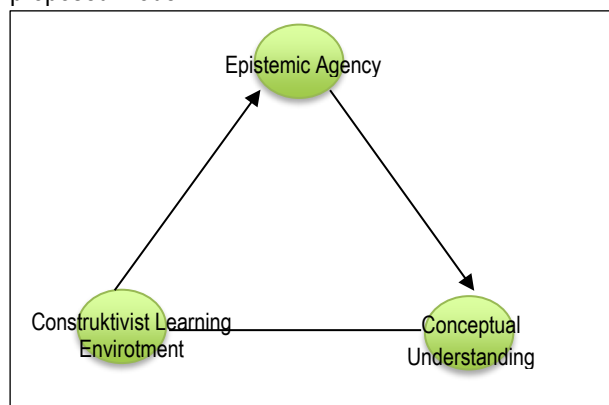


Figure 3. Structural equation model (SEM) illustrating the mediating role of epistemic agency in the relationship between constructivist learning environment and students' conceptual understanding.

Qualitative Findings

Thematic analysis of interview data identified three overarching themes contributing to persistent misconceptions:

1. Limited Dialogic Space – Students reported few opportunities to engage in open discussions or clarify misconceptions, often resulting in superficial understanding.
2. Lack of Contextualization – Abstract chemistry concepts were frequently presented without connections to real-life contexts, making them difficult to internalize.
3. Teacher Dominance – Classroom dynamics were characterized by strong teacher control, restricting students' active participation in knowledge construction.

These findings align with theoretical perspectives emphasizing the need for dialogic, student-centered environments to nurture epistemic agency.

3.2. Discussion

The results collectively demonstrate that epistemic agency plays a pivotal mediating role in shaping students' conceptual understanding within constructivist chemistry classrooms. This finding is consistent with prior evidence from Western contexts (Eriksson & Lindberg, 2016; González-Howard & McNeill, 2020; Kang, 2024), yet it offers new insights from Southeast Asia, where cultural norms often restrict classroom dialogue (Mohammed & Kinyó, 2022).

When juxtaposed with global studies, the Indonesian context reveals both similarities and contrasts. Comparable to findings by Fraser (2012) in Australia, constructivist environments positively correlate with conceptual understanding. However, Indonesian students exhibited relatively lower levels of epistemic agency, suggesting that hierarchical classroom cultures may hinder the full realization of constructivist pedagogy.

When juxtaposed with findings from global studies, the Indonesian context reveals both convergences and divergences in how epistemic agency manifests in science classrooms. Similar to results reported in Western countries, constructivist environments tend to foster deeper conceptual understanding; however, the levels of student voice and dialogic engagement observed in Southeast Asia remain comparatively lower. This discrepancy is not solely a pedagogical issue but is deeply rooted in cultural norms

that shape classroom interactions. Recent evidence from a systematic review further underscores that definitions and expressions of student agency vary widely across cultural contexts, with Asian settings often characterized by hierarchical relationships that constrain students' active participation (Inouye et al., 2023). These findings highlight the need for culturally responsive interventions to enhance agency and support meaningful conceptual change.

These findings have important implications for both pedagogy and policy. At the classroom level, teachers should prioritize dialogic, student-centered practices that allow learners to voice their ideas, negotiate meanings, and actively participate in constructing knowledge. At the policy level, this aligns with the OECD Learning Compass 2030, which positions student agency as a core competency for future education systems, emphasizing learners' ability to set goals, reflect critically, and act responsibly within diverse contexts (OECD, 2019). Consequently, incorporating agency-oriented strategies into curriculum reforms and teacher professional development can bridge gaps between current practices and the demands of global competency frameworks such as PISA 2025.

From a pedagogical perspective, the results advocate for strategies that expand dialogic spaces, integrate real-life contexts, and empower students' voices in chemistry classrooms. Such practices align with OECD (2019) recommendations and the PISA 2025 agenda, both of which emphasize agency and global competencies as essential learning outcomes.

4. CONCLUSION

By integrating Rasch modeling with diagnostic assessment and qualitative inquiry, the research validates both the measurement instrument and its theoretical underpinnings across a Southeast Asian context.

From a theoretical perspective, these findings reinforce the notion that epistemic agency is not merely an individual attribute but a culturally embedded construct shaped by classroom practices and educational policies. This observation aligns with recent evidence indicating that expressions of student agency vary across cultural contexts and are influenced by sociocultural factors that mediate how learners engage in knowledge construction (Inouye et al., 2023). Moreover, the study's results

resonate with the OECD Learning Compass 2030, which frames student agency as a foundational competency for future education, linking it directly to global competency frameworks such as PISA 2025 (OECD, 2019).

Pedagogically, the findings underscore the importance of expanding dialogic spaces, promoting student-centered approaches, and contextualizing abstract concepts to reduce misconceptions and deepen conceptual understanding. For teachers, this requires cultivating environments where students are encouraged to voice their perspectives, negotiate meanings, and participate actively in constructing knowledge.

Policy-wise, embedding agency-oriented strategies into curriculum reforms and teacher professional development programs is essential to bridge the gap between traditional practices and global educational standards. Such strategies are consistent with both national education reforms, including Indonesia's Merdeka Belajar, and international agendas that emphasize student agency as a driver of lifelong learning and innovation.

Taken together, this study contributes to the theoretical advancement of the dual-path learning framework by empirically embedding epistemic agency as a key mechanism in conceptual change. Simultaneously, it provides actionable insights for educators and policymakers seeking to enhance science education outcomes in culturally diverse settings.

5. ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Direktorat Riset dan Pengabdian Masyarakat (DRPM), Kemendikisaintek Republik Indonesia, and LPPM Universitas Negeri Gorontalo for providing financial support through the 2025 Research Grant Program, which made this study possible. The authors also extend their appreciation to the participating schools, teachers, and students for their valuable contributions during the research process.

During the preparation of this manuscript, the authors utilized ChatGPT solely to improve the clarity and coherence of the writing. All generated content was critically reviewed, edited, and validated by the authors, who take full responsibility for the integrity and originality of the final manuscript.

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