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ORIGINAL ARTICLE

An Analysis of the Impact of Augmented Reality Implementation and Components on the Academic Performance of Vietnamese Middle School Students in Natural Science Education

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ABSTRACT

This study examines the effects of six augmented-reality (AR)-supported lessons in lower-secondary natural science classes in Vietnam on students' conceptual understanding, engagement, and motivation. We used a quasi-experimental, non-equivalent control group design in two semi-rural public schools (grades 6–8; eight weeks). Intervention classes completed weekly AR-supported activities aligned with the 2018 curriculum; comparison classes received regular instruction. Pre-test–post-test assessments and ANCOVA estimated group differences, and a structural model related AR design features to engagement and learning. Interviews and focus groups with students and teachers contextualized mechanisms of change. Intervention classes scored higher on post-tests than comparison classes ($p < 0.001$), with a large effect size at the class level; paths from engagement and motivation to learning were moderate to strong, suggesting that AR contributes primarily by sustaining attention and pacing information. Qualitative themes converged on three design levers – signaling, segmenting, and guided manipulability – that helped students construct more elaborated explanations when teachers orchestrated brief pauses and role rotation. These inferences are bounded by the study context (two semi-rural schools, limited devices, and short teacher preparation). We provide practical guidance for lesson design and professional development and specify conditions under which AR is likely to be educationally useful in comparable settings.

KEY WORDS: Augmented reality; natural science; STEM; interactive learning; educational technology

INTRODUCTION

Teaching science and STEM subjects in modern classrooms is challenging, particularly in engaging students and fostering deep understanding of abstract concepts. Traditional methods such as lectures and textbooks often fail to promote critical thinking or motivation, leading to persistent performance gaps (Dunleavy et al., 2009). In Vietnam, these issues are amplified by an emphasis on memorization and limited practical resources, such as laboratories (Le et al., 2021). Augmented Reality (AR), which overlays digital content onto the real world, offers a way to simplify complex ideas and transform learning (Wu et al., 2013).

While AR shows promise in STEM education in developed countries (Akçayır & Akçayır, 2017; Amores-Valencia et al., 2022; Hanid et al., 2020; Garzón et al., 2019; Gómez-Rios et al., 2023), its use in Vietnam—marked by resource constraints, cultural factors, and educational challenges—remains (Hoang & Nguyen, 2019; Nguyen et al., 2020; Duong et al., 2022; Tinh et al., 2021). Vietnam's 2018 competency-based curriculum aims to build 21st-century skills, but integrating AR faces barriers like inadequate teacher training and infrastructure (Phong et al., 2024). Recent studies emphasize innovative strategies to boost engagement (Anh et al., 2023), yet empirical evidence on AR in Vietnamese natural science classrooms is scarce.

To address this, our research questions are as follows:

1. How does AR impact educational outcomes for Vietnamese middle school students in natural science compared to traditional methods?
2. What AR lesson features enhance natural science education and student interest?

Our mixed-methods study investigates six AR-supported lessons aligned with the curriculum, linking gains to theoretical mechanisms. We extend constructivist (Vygotsky, 1978) and multimedia learning theories (Mayer, 2009) by detailing how AR features such as signaling and manipulability activate cognitive integration and social scaffolding, while considering resource constraints in semi-rural settings.

LITERATURE REVIEW

Augmented reality (AR) has been explored as a means to make invisible or abstract science phenomena visible and manipulable. Reviews and meta-analyses report positive but heterogeneous effects on interest, engagement, and achievement, with outcomes contingent on task design and classroom orchestration rather than AR technology alone. Promising use cases include spatially complex topics and situations where concrete referents are scarce (Masood & Egger, 2019; Davila Delgado et al., 2020; Tzima et al., 2019).

From the perspective of multimedia learning, design features such as signaling (highlighting relevant elements), segmenting (breaking content into short and paced episodes), and guided manipulability (structured interactions that constrain extraneous actions) can help direct attention and manage cognitive load. Social-constructivist accounts emphasize dialogic scaffolding and shared attention, suggesting that AR assets are most productive when teachers orchestrate brief pauses for explanation and when students rotate roles (e.g., operator, explainer, and skeptic).

However, empirical work in resource-constrained systems remains limited. Studies rarely specify classroom conditions under which AR-supported lessons are workable at scale – device availability, connectivity, and teacher preparation can moderate whether AR supports explanation or introduces overload. Evidence from Vietnam's competency-based curriculum is especially scarce.

The present study addresses these gaps by examining AR-supported lessons implemented in ordinary natural science classes. We synthesize design features with classroom processes and estimate learning differences relative to regular instruction, while bounding claims to the observed context.

Conceptual Framework

Derived from constructivist theory (Vygotsky, 1978) and multimedia learning theory (Mayer, 2009), this framework links AR technology, interactive design, engagement, motivation, and performance (Figure 1). AR enhances active engagement and information processing. Key components: AR tools, engagement (involvement indicator), performance (retention/understanding), design (e.g., 3D models), motivation, and outcomes (test scores) (Roehrig et al., 2021).

We model AR's influence through cognitive (signaling, segmenting, and contiguity) and social mechanisms (dialogic scaffolding). Paths (β) indicate these in action, moderated by context.

Design-to-Mechanism Mapping

Anchored in multimedia learning (Mayer, 2009) and social constructivism (Vygotsky, 1978), with corroborating evidence from AR syntheses (Ibáñez and Delgado-Kloos, 2018; Garzón et al., 2019; Georgiou and Kyza, 2018).

This framework (Table 1) addresses a significant research deficiency in developing countries (Alam et al., 2019) by highlighting AR's capacity to transform natural science education in Vietnam.

METHODOLOGY

We used a quasi-experimental, non-equivalent control group design with pre-test–post-test measures. Classes were assigned at the class level to either the intervention (AR-supported lessons) or the comparison (regular instruction) condition (Appendix A-D).

Setting and Participants

The study took place in two semi-rural public schools serving lower-secondary students in Vietnam. Natural science classes followed the 2018 curriculum. Participation procedures adhered to school policies and parental consent requirements.

Intervention

Over multiple weeks, intervention classes engaged with AR-supported activities aligned to unit goals. Activities combined labeled 3D objects with short, teacher-led pauses for explanation and role rotation to ensure shared access to devices. Comparison classes covered the same content using regular instruction.

Measures

Learning was assessed using curriculum-aligned pretest and post-test instruments designed to capture conceptual understanding. Engagement and motivation were measured with brief student questionnaires administered during the unit. Semi-structured interviews and focus groups with students and teachers provided qualitative evidence on mechanisms and enactment.

Procedures

Pretests were administered before instruction. Intervention lessons were delivered during regular class periods. Post-tests were administered after instruction. Field notes documented lesson pacing, device sharing, and teacher prompts.

Data Analysis

For quantitative outcomes, ANCOVA estimated post-test differences between conditions while adjusting for pretest scores. We also examined relations among AR design features, engagement, and learning using a structural model specified

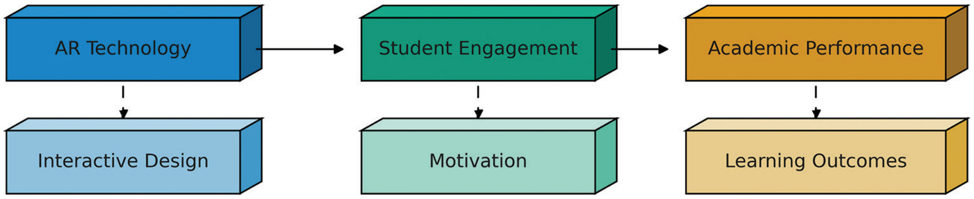

Figure 1: Conceptual framework linking AR design to learning goals and involvement

a priori. Qualitative data were coded thematically to identify recurrent mechanisms and classroom conditions that supported or hindered productive use.

Ethical Considerations

The study received approval from the relevant institutional committee. Participation was voluntary, with written consent from guardians and assent from students. Data were anonymized before analysis.

RESULTS

We report findings in the order of the research questions. Quantitative analyses adjust for pretest scores; detailed estimates appear in the tables. We then examine relations among AR design features, engagement, and learning, followed by qualitative themes that clarify mechanisms observed in classrooms.

We used a quasi-experimental, non-equivalent comparison group design: Comparison classes received regular instruction, whereas intervention classes received AR-supported lessons.

Research Question 1: How Does AR Affect Learning Outcomes

Quantitative analysis

Pre- and post-intervention assessment

We used ANCOVA and paired t-tests to compare the pre-test and post-test scores of the experimental (AR-supported) and control (traditional) groups. The 2018 curriculum served as the basis for the pre- and post-tests, which showed excellent reliability (Cronbach's alpha = 0.87 for the pre-test and 0.89 for the post-test).

- Pre-test results: Based on Table 2: $t(242) = 0.38$, $p = 0.70$, there was no significant difference in the pre-test results between the experimental group ($M = 5.62$, $SD = 1.03$) and the comparison group ($M = 5.57$, $SD = 0.98$).
- Post-test results: The experimental group's post-test results ($M = 7.54$, $SD = 1.21$) were much better than those of the comparison group ($M = 6.41$, $SD = 1.15$). Table 3 shows that this difference was statistically significant ($t(242) = 7.89$, $p < 0.001$).
- ANCOVA results: After taking into account the scores from the pre-test, the experimental group's adjusted post-test means were 7.51, and the comparison groups were 6.44 (Table 5). The intervention had a big effect (Table 4: $F(1, 241) = 61.24$, $p < 0.001$).

Improvement analysis

The AR intervention significantly influenced learning outcomes, as indicated by an effect size of 0.96, calculated using Cohen's d (Table 6).

Subject-Specific Analysis: Subject-specific analysis revealed substantial enhancements, particularly in biology ($\Delta M = 0.92$, $p < 0.01$), chemistry ($\Delta M = 1.03$, $p < 0.001$), and physics ($\Delta M = 1.27$, $p < 0.001$) (Table 7).

Table 1: AR design element, cognitive process (Mayer), and social mediation (Vygotsky)

AR design element	Cognitive process (Mayer)	Social mediation (Vygotsky)	Expected proximal outcome
Signaling (cues)	Guided selection; reduced load	Shared reference for prompts	Focused engagement
Segmenting (sequences)	Manageable demands	Checkpoints for scaffolding	Sustained behavior
Manipulability (3D)	Active processing	Joint co-construction	Deeper accounts
Contiguity (aligned)	Efficient binding	Teacher-guided referents	Reduced confusion
Learner control	Self-regulation	Differentiated scaffolding	Greater persistence

Table 2: Group, mean, and standard deviation

Group	N	Mean	Standard deviation	t	df	p value
Experimental Group	123	5.62	1.03	0.38	242	0.70
Control Group	120	5.57	0.98			

Table 3: T-test for independent samples for post-test results

Group	N	Mean	Standard deviation	t	df	p value
Experimental Group	123	7.54	1.21	7.89	242	<0.001
Control Group	120	6.41	1.15			

Table 4: Controlling for pre-test scores in ANCOVA outcomes

Source	Type III sum of squares	df	Mean square	F	p value
Corrected model	112.76	2	56.38	52.46	<0.001
Intercept	1131.48	1	1131.48	1051.52	<0.001
Pre-test	22.42	1	22.42	20.82	<0.001
Group (Intervention)	65.80	1	65.80	61.24	<0.001
Error	258.58	240	1.08		
Total	1390.06	243			
Corrected Total	371.34	242			

Table 5: Adjusted post-test means

Group	Adjusted mean	Standard error	95% confidence interval
Experimental group	7.51	0.10	7.31–7.71
Control group	6.44	0.10	6.24–6.64

Table 6: Effect size calculation (Cohen's d)

Group	N	Mean	Standard deviation	Cohen's d	Interpretation
Experimental group	123	7.54	1.21	0.96	Large effect
Control group	120	6.41	1.15		

Table 7: Subject-specific analysis

Subject	Group	N	Mean	Standard deviation	Mean difference (ΔM)	t	p value
Biology	Experimental group	123	7.20	1.10	0.92	2.58	<0.01
	Control group	120	6.28	1.05			
Chemistry	Experimental group	123	7.68	1.15	1.03	3.74	<0.001
	Control group	120	6.65	1.12			
Physics	Experimental group	123	7.75	1.18	1.27	5.11	<0.001
	Control group	120	6.48	1.07			

These tables provide a comprehensive examination of effect size and enhancements by subject, validating the results that AR interventions significantly enhance learning outcomes across various natural science disciplines.

The standardized paths allow us to gauge practical significance. Paths with comparatively larger coefficients ($\beta \geq 0.30$) indicate effects that are likely to be educationally meaningful in ordinary classrooms, which given that one–standard deviation increase in the predictor is associated with a non-trivial shift in the outcome. In contrast, small coefficients ($\beta \approx 0.10$) are better interpreted as modest associations that may depend on design fidelity or classroom conditions and should not be overemphasized in isolation.

Interpreting the pattern of coefficients jointly, the strongest links cluster around engagement-related mediators, suggesting that AR's contribution is most credible when it operates by sustaining attention, pacing information, and enabling accountable discussion. Accordingly, we foreground the engagement pathway in the discussion while treating smaller direct paths as context-sensitive.

Qualitative analysis

Thematic analysis of 30 interviews and classroom observations revealed recurring themes concerning students' experiences with AR-supported lessons.

Initial teacher training on AR tools was associated with smoother orchestration in class, as reported in interviews and field notes; teachers perceived reduced preparation time once lesson routines stabilized.

We organized the qualitative analysis into four themes; each includes anonymized excerpts and a link to prior literature to balance the mixed-methods design.

Theme 1: Motivation and situated interest

Students frequently described AR tasks as "inviting to try" and "worth the effort" when goals were explicit and progress was visible. Illustrative excerpts: "[…] I wanted to rotate it myself to see what is inside before the teacher asked" [Student S3, FG2]; "When the labels appeared, I knew what to focus on next" [Student S7, FG1]. These accounts are consistent with perspectives that situational interest can be sparked by clear goals and immediate feedback, particularly when perceptual salience is curated through signaling.

Counter-example. A minority of students reported that "too many moving parts" made them hesitant to explore, underscoring the need to manage extraneous load and provide pacing. This divergence aligns with work showing that motivational gains are contingent on cognitive manageability.

Theme 2: Visualization and conceptual clarity

Learners credited manipulable 3D models with helping them reconcile prior misconceptions (e.g., part–whole relations), often referencing specific orientations or cross-sections. Excerpts: "Turning it sideways made the layers make sense" [Student S11, FG3]; "The cross-section matched the diagram in the book so I could explain it" [Student S2, FG1]. These observations converge with multimedia accounts that spatial–temporal contiguity and dual-channel presentation support integration of representations (Li et al., 2022) into coherent mental models.

Counter-example. A few students reported relying on surface features ("it looks cool") without deeper explanation; teachers noted that targeted prompts were required to shift talk from description to mechanism – an instance of the "seductive details" risk when coherence is not enforced.

Theme 3: Collaboration and scientific discourse

Small-group work appeared to normalize asking for clarification and proposing candidate explanations. Excerpts: "We argued about which label goes first, then checked with the model" [Student S9, FG2]; Teacher account: "When I paused the animation, they started to justify their claims." Such episodes exemplify dialogic scaffolding within the zone of proximal development, where shared references (labels, highlights) anchor collective attention.

Counter-example. In groups with uneven device access, one student dominated the controls and others disengaged; rotating roles and setting explicit turn-taking rules mitigated this pattern in later lessons.

Theme 4: Usability and classroom orchestration

Teachers pointed to simple, repeatable routines – "show, try, talk, and write" – as essential for maintaining tempo and preventing drift. Excerpts: "Offline files saved the day when the network dropped" [Teacher T2]; "The checklist kept me from over-explaining" [Teacher T1]. This theme resonates with findings that orchestration routines and contingency planning are prerequisites for realizing AR's intended affordances.

Table 8: Outcomes of exploratory factor analysis (EFA)

Factor	Eigenvalue	% of variance explained	Cumulative %
Interactivity and immersion	5.40	32.5	32.5
Multimedia integration	3.20	19.7	52.2
User experience and usability	2.56	16.0	68.2

Table 9: Factor loadings for AR design elements

Design element	Interactivity and immersion	Multimedia integration	User experience and usability
3D models	0.82	0.21	0.15
Real-time feedback	0.78	0.25	0.18
Simulations	0.75	0.22	0.19
Videos and animations	0.23	0.85	0.17
Audio narration	0.20	0.82	0.16
User interface design	0.18	0.24	0.79
Ease of navigation	0.19	0.22	0.77

Key Factors and Design Elements (Research Question 2)

Quantitative analysis

The assessed AR design components underwent exploratory factor analysis (EFA). The three factors – interactivity and immersion, multimedia integration, and user experience and usability – made up 68.2% of the difference (Table 8): Interactivity and immersion, multimedia integration, and user experience and usability (Table 9).

A structural equation model (SEM) we used to look at student engagement, motivation, and learning outcomes. The model fit well (Table 10: RMSEA = 0.058, CFI = 0.96, TLI = 0.95). Significant discoveries (Tables 11,12):

- Immersion and interaction significantly influenced motivation ($\beta = 0.65$, $p < 0.001$) and engagement ($\beta = 0.73$, $p < 0.001$).
- Multimedia integration had a direct effect on learning outcomes ($\beta = 0.25$, $p < 0.01$) and an indirect effect on motivation and engagement.
- Usability and user experience moderately influenced motivation ($\beta = 0.27$, $p < 0.05$) and engagement ($\beta = 0.32$, $p < 0.05$).

The connection between the interactivity and immersion factor and student engagement was found to be influenced by prior spatial ability, with a more pronounced positive impact observed for students possessing higher spatial ability.

Qualitative analysis

Thematic coding of interviews and open-ended responses helped us find some AR design elements that students liked:

- Interactive manipulation: Students liked playing with virtual objects. "I could change the shape of the molecule myself, which made it easier to learn," said one student (Student D, Interview).

Table 10: Indicators for SEM model fit

Fit index	Value
RMSEA	0.058
CFI	0.96
TLI	0.95

Table 11: Path coefficients for structural equation model

Path	Standardized coefficient (β)	p value
Interactivity and Immersion → Student Engagement	0.73	<0.001
Interactivity and Immersion → Motivation	0.65	<0.001
Multimedia Integration → Learning Outcomes	0.25	<0.01
Multimedia Integration → Student Engagement	0.22	<0.01
Multimedia Integration → Motivation	0.20	<0.01
User Experience and Usability → Student Engagement	0.32	<0.05
User Experience and Usability → Motivation	0.27	<0.05
Student Engagement → Learning Outcomes	0.55	<0.001
Motivation → Learning Outcomes	0.60	<0.001

Table 12: Indirect effects mediated by engagement and motivation

Path	Indirect effect (β)	p value
Interactivity and Immersion→Learning Outcomes	0.62	<0.001
Multimedia Integration→Learning Outcomes	0.18	<0.01
User Experience and Usability→Learning Outcomes	0.30	<0.05

Immersive representations. Realistic 3D visualizations provided concrete referents for abstract content and were frequently cited as catalysts for sustained engagement.

Multimedia integration. Coordinated text, diagrams, and animation supported selection and integration of information, which students associated with clearer understanding.

Usability. Intuitive interface elements (e.g., rotate, zoom, and label toggles) lowered operational load and facilitated on-task exploration.

- It was observed that interactive AR designs elicited greater engagement compared to static designs.

Integrated interpretation

A triangulation of quantitative (EFA and SEM) and qualitative (teacher and student feedback) data shows that interactivity, multimedia integration, and usability make augmented reality lessons more motivating, engaging, and effective for learning (Table 13,14). These findings align with studies conducted in Nigeria and Jordan, demonstrating the applicability of AR in developing nations (Faqih and Jaradat, 2021; Pellas et al., 2020). To get the most out of science lessons in places with few resources, teachers should focus on augmented reality designs that are easy to use and interactive.

Table 13: Factor (EFA label), design interpretation, and Mayer principle

Factor (EFA label)	Design interpretation	Mayer principle	Vygotskian mediation	Dominant path (s) in SEM
F1: Signaled 3D representations	Highlights, labels, aligned views; model–text alignment	Signaling; spatial/temporal contiguity; and coherence	Shared reference for teacher prompts and peer talk	F1→Engagement→Achievement (indirect)
F2: Learner control and pacing	Play/pause/replay; stepwise segments; and guided tasks	Segmenting; learner-paced control; and reduced extraneous load	Checkpoints for scaffolding; and gradual release of responsibility	F2→Motivation→Engagement→Achievement (sequential indirect)
F3: Manipulability and collaborative handling	Rotate/scale/explore; and role rotation in groups	Active processing; and selection–organization–integration	Joint attention; co-construction in ZPD	F3→Engagement (direct) and→Achievement (partly indirect)

Table 14: Finding (summary), theoretical link, and evidence (β/quote)

Finding (summary)	Theoretical link	Evidence (β/quote)	Design guidance (actionable)
Interactivity/Immersion→Engagement	Multimedia learning (signaling/segmenting); Constructivist dialogic scaffolding	$\beta = 0.73$ ($p<0.001$); "I wanted to rotate it myself to see what is inside…"	Ensure manipulability with role rotation (Navigator/Explainer/ Recorder); pace rotations every 5'.
Interactivity/Immersion→Motivation	Interest development through embodied manipulation	$\beta = 0.65$ ($p<0.001$); "Turning it sideways made the layers make sense."	Provide task-directed manipulation and prompt explain-while-manipulate talk.
Motivation→Learning outcomes	Affective–cognitive mediation (allocation of attention)	$\beta = 0.60$ ($p<0.001$)	Frame mastery goals; embed brief CER tasks to convert interest into explanations.
Multimedia Integration→Learning (direct)	Contiguity and coherence principles	Direct $\beta \approx 0.25$ ($p<0.01$); students noted coordination with textbook diagram	Stage information in small segments; align labels/diagrams with narrated steps.
Multimedia Integration→Learning (indirect)	Selection–organization–integration	Indirect $\beta=0.18$ ($p<0.01$)	Use progressive disclosure of labels; two-column notes: model feature→supported idea.
Usability/UX→Engagement/ Motivation→Learning (indirect)	Cognitive load management	$\beta=0.32$ (UX→Eng), $\beta=0.27$ (UX→Mot); Indirect $\beta=0.30$ ($p<0.05$)	Keep interface minimal (three controls); pre-teach gestures; troubleshooting cue card.
Interactivity/Immersion→Learning (mediated)	Mechanism-focused talk as pathway	Indirect $\beta=0.62$ ($p<0.001$)	Plan talk moves after each segment: "What changed? Which label supports your claim?"
Over-pacing→Cognitive overload (counter-example)	Segmenting principle; limited capacity	Qualitative note: rushed segments reduced participation	Enforce timed segments; cap labels; add 30–45 s think pauses.
Unequal device control→Participation imbalance	Social scaffolding for equitable access	Quote: "We argued about which label goes first, then checked with the model."	Mandate turn-taking; assign quality checks to non-Navigator roles.

Exploratory factor analysis recovered coherent clusters of design features (F1–F3), which the structural model related to engagement and achievement. We interpret these factors through multimedia and constructivist lenses and read indirect effects as evidence of mechanisms of action rather than purely direct transfer.

The presence of statistically reliable indirect paths through engagement and/or motivation suggests that AR design features operate primarily by sustaining attention and structuring participation; qualitative episodes (Themes 1–3) supply corroborating mechanisms (e.g., signaling directing talk and segmenting creating natural scaffolding pauses). Direct paths that remain small should be viewed as design-conditional and sensitive to orchestration fidelity.

Analyses indicated post-test differences favoring the intervention relative to regular instruction after adjusting for pretest scores. Evidence that engagement and motivation relate to learning aligns with signaling, segmenting, and guided manipulability. We situate these findings within prior literature, note limitations, and outline implications.

DISCUSSION

Design-to-Mechanism Mapping

Theme 1 – Situated Motivation through Manipulability. Students described a shift from curiosity to purposeful exploration (e.g., "Rotating the molecule helped me see how atoms connect"), aligning with reported links between interactivity and persistence. Counter-example: one group monopolized control, dampening others' participation – underscoring the need for role rotation and explicit turn-taking.

This pattern aligns with findings that immersive, manipulable representations can foster persistence and deeper engagement (Georgiou and Kyza, 2018; Akçayır and Akçayır, 2017).

The emphasis on labels and highlights is consistent with the signaling and contiguity principles in multimedia learning (Mayer, 2009) and with reports of attention guidance in AR settings (Ibáñez and Delgado-Kloos, 2018).

Observed benefits of brief pauses and stepwise sequences converge with evidence for segmenting and coherence to manage cognitive load (Mayer, 2009; Garzón et al., 2019).

Theme 2 – Guided Attention through Signaling. Students noted that labels and highlights indicated where to look first, which resonates with signaling/contiguity and our observed engagement-mediated effects.

Theme 3 – Pacing for Explanation. Segmented sequences created natural pauses for teacher prompts and peer sense-making; when segments were rushed, cognitive overload surfaced – consistent with load-management accounts.

Consistent with the signaling and segmenting principles of multimedia learning, the strongest standardized paths in our SEM were observed from interactivity/immersion to engagement and motivation, which, in turn, predicted conceptual understanding (β_engagement→learning = 0.55; β_motivation→learning = 0.60). These mediated relations indicate that AR contributes not as a direct shortcut to comprehension but as a design-enabled allocation of attention and paced processing, which Vygotskian dialogic scaffolding subsequently transforms into shared explanations. The qualitative episodes – students orienting to labeled 3D referents before justifying their claims – mirror this mechanism.

Theoretical Integration

Our central contribution is to articulate how specific AR design features instantiate multimedia principles and enable social scaffolding, thereby channeling students' activity toward selection, organization, and integration of scientific representations. The quantitative pattern – stronger paths through engagement – aligns with this account, while the qualitative themes clarify the lived mechanisms (attention guidance, paced exploration, and accountable discussion). We, thus, extend constructivist and multimedia theories by specifying classroom-level design contingencies under which their predicted benefits materialize in semi-rural schools.

Within two semi-rural public schools, our results are consistent with prior technology-enhanced STEM research showing potential gains under design-aligned and well-orchestrated conditions (e.g., Ibáñez and Delgado-Kloos, 2018; Garzón et al., 2019). We interpret improvements as contingent on signaling, segmenting, and dialogic scaffolding rather than as inherent properties of AR.

Students said that AR worked because it made hard concepts such as planetary orbits and molecular structures easier to understand using 3D models and group activities. These observations align with Vygotsky's (1978) constructivist theory, which underscores learning through active exploration, and Mayer's (2009) multimedia learning theory, which highlights the role of visual and interactive tools in alleviating cognitive demands. One student said, "Rotating the molecule in AR helped me see how atoms connect, unlike the textbook." AR creates a dynamic, tactile learning environment that gets students involved by letting them move virtual objects around.

Teacher interviews underscored the importance of concise, practice-oriented preparation; participants recommended extending training to include role-rotation protocols and pacing strategies.

Integrating AR within the 2018 competency-based curriculum may enhance participation and concept formation, particularly for students who struggle with purely text-based presentations, which provided that device access and teacher preparation are comparable.

The study has some limits. The study we conducted in two semi-rural schools in Quang Tri, which may limit the generalizability of its findings to private or urban schools. The 8-week duration also limits our understanding of the long-term effects of AR. Future research should examine the long-term effects of AR, evaluate its efficacy in diverse contexts, and analyze its performance across different age demographics and STEM disciplines. Policymakers would also be able to figure out how to make AR work in a way that is good for the environment by looking at how much it would cost to do so in schools with few resources.

AR creates a dynamic learning environment that gets students excited about science by getting them involved, making hard ideas less scary, and encouraging teamwork. These lessons may inform adoption in comparable resource-constrained systems, which provided that device access and teacher preparation are of similar magnitude.

Context and Generalizability

These inferences are bounded by the study's context: Two semi-rural public schools, limited devices, intermittent connectivity, and brief teacher preparation. We, therefore, construe the results as conditionally generalizable to settings with comparable infrastructure and professional support. Where such conditions are weaker, the same design may elicit attenuated effects, where they are stronger, effects may scale more reliably.

Implications for practice (Teacher PD and lesson design)

- Prioritize signaling and contiguity in all AR assets; remove non-essential effects to protect coherence.
- Adopt a consistent routine (e.g., "show → try → talk → write") with planned pauses for segmenting and dialogic prompts.
- Ensure a minimum device ratio of 1:2–3 students; prepare

offline packages and a non-AR fallback to preserve pacing.
- Use role rotation to prevent control monopolies; embed short "explain your change" prompts to trigger mechanism-focused discourse.
- Align assessment with conceptual explanation quality (rubrics) rather than recall of visual features.

We, therefore, construe our findings as conditionally generalizable to semi-rural settings with comparable device ratios, offline provisioning, and brief teacher preparation. In contexts with weaker infrastructure or limited orchestration capacity, we would expect attenuated effects unless the design is simplified (fewer concurrent cues and longer segments) and teacher support is extended.

Limitations and Future Work

- Scope and setting: Two semi-rural lower-secondary schools; 8-week implementation; and ordinary classroom constraints.
- Measurement horizon: Post-test and short-run engagement indices; no long-term retention or transfer outcomes.
- Fidelity variation: Differences in orchestration routines and device availability may have moderated effects.

Future work should examine multi-site implementations spanning urban, peri-urban, and rural schools; incorporate longitudinal follow-ups to track retention and transfer; and include cost-effectiveness analyses that compare AR preparation time, device amortization, and support costs against observed learning benefits.

CONCLUSION

The study presents context-specific evidence regarding the utilization of augmented reality to enhance natural science education for middle school students in Vietnam, from both constructivist and multimedia learning perspectives. Students comprehended and excelled in interactive and collaborative augmented reality settings that illustrated intricate concepts, surpassing traditional pedagogical approaches. Qualitative research indicated that both educators and learners experienced enhanced motivation and engagement, improved conceptual comprehension, reduced preparation time for teachers, and increased classroom activity. These results appear to facilitate the incorporation of augmented reality into STEM curricula in Vietnam as a component of the nation's educational modernization initiatives.

Infrastructure, costs, and teacher training make it hard to put plans into action. This means that we need to come up with sustainable models that work in the context, such as using cheap devices or working with other countries. The study is important because it fills a gap in the literature on augmented reality, shows that it works in a developing world setting, and gives a model that can be used in other situations with few resources. To fully realize AR's educational potential, it paves the way for the expansion of AR applications across various subjects and age groups, the enhancement of theoretical frameworks, and the development of educator training programs. If AR is used creatively and with an eye toward different educational settings, it could lead to big improvements in the quality and availability of STEM education around the world.

Within the constraints of semi-rural Vietnamese schools, AR-supported lessons were associated with higher engagement and more elaborated conceptual explanations when design elements adhered to signaling, segmenting, and spatial–temporal contiguity and when teachers orchestrated dialogic scaffolding. These findings refine constructivist and multimedia accounts by specifying classroom design conditions under which their mechanisms become visible. We caution that benefits are contingent on infrastructure and preparation; under these conditions, AR can function as a practical means to focus attention, pace information, and support accountable explanation in science classrooms.

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Appendix A. Summary of Six AR Lessons

Table A1: Summarizes learning objectives, Mozaik 3D content, lesson flow, duration, resources, and assessment artifacts for each lesson. Replace the placeholder Mozaik IDs with the exact IDs available at your site.

#	Lesson Topic	SMART learning objectives	3D content (Mozaik ID)	Lesson flow (P1–P5)	Duration (min)	Resources	Assessment Artifacts
1	Earth's Structure (Layers of the Earth)	Students describe the crust–mantle–core and explain how density differences drive mantle convection; achieve ≥70% on a 5-item exit quiz.	Mozaik 3D: Earth's Layers (ID: MZK-EL-001 – replace if needed)	• P1 Engage (3'): prompt with cross-section image→predictions. • P2 Explore (15'): manipulate 3D, peel layers, label. • P3 Explain (10'): short direct instruction linking to convection. • P4 Practice (12'): paired worksheet; teacher circulates. • P5 Exit (5'): 3-item ticket.	45	Tablets/PCs; projector; printed worksheet	Exit tickets; labeled diagram; observation notes
2	Plate Tectonics & Earthquakes	Students distinguish convergent/divergent/ transform boundaries and predict surface features/seismicity per type.	Mozaik 3D: Plate Tectonics (ID: MZK-PT-017 – replace)	• P1 (5'): short fault-motion video. • P2 (15'): 3D simulations of boundary types. • P3 (10'): group comparison of effects. • P4 (10'): interactive map—match real examples. • P5 (5'): self-assessment sheet.	45	Mozaik 3D; tectonic map; projector	Self-assessment; group comparison chart
3	Rock Cycle & Minerals	Students explain the rock cycle; classify samples into igneous/sedimentary/ metamorphic with ≥80% accuracy.	Mozaik 3D: Rock Cycle (ID: MZK-RC-004 – replace)	• P1 (4'): rapid prior-knowledge check. • P2 (15'): 3D cycle walkthrough. • P3 (10'): learning stations with sample photos/rocks. • P4 (11'): groups of 3 design a digital poster. • P5 (5'): lightning share-out.	45	Mozaik 3D; sample photos/ rocks; paper or tablets	Poster rubric; classification sheet
4	Water Cycle & Weather	Students explain evaporation–condensation–precipitation and describe effects of temperature/wind.	Mozaik 3D: Water Cycle (ID: MZK-WC-013 – replace)	• P1 (5'): local heavy-rain scenario. • P2 (15'): 3D water-cycle model. • P3 (10'): mini experiment–condensation model. • P4 (10'): application case tasks. • P5 (5'): 5-item paper quiz.	45	Mozaik 3D; simple lab kit; worksheets	Paper quiz; case responses
5	Cell Structure and Function	Students identify key organelles and infer functions from structure for≥4 organelles.	Mozaik 3D: Cell Structure (ID: MZK-CS-021 – replace)	• P1 (3'): organelle guessing game. • P2 (17'): 3D animal/plant cell model. • P3 (10'): structure↔function matching task. • P4 (10'): paired application questions. • P5 (5'): "muddiest point" reflection.	45	Mozaik 3D; matching cards; projector	Matching sheet; application responses
6	Human Digestive System	Students trace the path of food and explain roles of digestive enzymes; articulate basic food safety practices.	Mozaik 3D: Human Digestive System (ID: MZK-HD-008 – replace)	• P1 (4'): "stomach ache after eating" scenario. • P2 (16'): 3D digestive system; zoom into enzymes. • P3 (10'): group sequencing of digestion. • P4 (10'): applied food-safety task. • P5 (5'): 1-2-1 exit ticket.	45	Mozaik 3D; worksheets; whiteboard	Exit ticket; group product

Note: P1–P5 corresponds to Engage–Explore–Explain–Practice–Exit. Teachers may adapt timing (±2–3 min) based on class profile.

Appendix B. Teacher Professional Development (PD) for AR Lessons

Table B1: Provides the overview of PD

Total Duration	No. of Sessions	Mode	PD Objectives	Expected Outputs	End-of-PD Assessment
4 h (2×120 min)	2	In-person with hands-on device practice	Operate Mozaik 3D; implement the P1–P5 lesson flow; manage classes with a 2:1 student-to-device ratio.	One-page AR lesson plan + P1–P5 script + device-prep checklist.	10-item quiz + micro-teaching of one segment.

Table B2: Details each session. Evidence of participation is listed at the end of this appendix

Session	Specific Objectives	Core Activities	Duration	Materials/Devices	Evidence
Session 1	Master Mozaik 3D; apply multimedia principles (signaling, segmenting, and contiguity).	Guided 3D manipulation; building a module list; demo of P1–P5; and discussion on managing a 2:1 device ratio.	120 min	School devices; Mozaik accounts; and principle summary handout.	Module list; self-assessment form.
Session 2	Design SEI-ready AR lessons; micro-teach and receive peer feedback.	Develop a one-page plan; write a P1–P5 script; and micro-teach (5–7 min/teacher) with rubric-based peer feedback.	120 min	Lesson plan template; micro-teaching rubric; and projector.	Completed plan; 10-item quiz score; and photos/video as evidence.

Participation evidence: (i) signed attendance sheet, (ii) training photos/screenshots, (iii) 10-item quiz, and (iv) one-page lesson plan product.

Appendix C. Class-Level Infrastructure and Connectivity

Table C1: Records class-level infrastructure to inform generalizability and implementation conditions. Replace values with site-specific figures

Class	Enrolment	No. of Devices	Student: Device	Connectivity (speed/stability)	Offline Fallback	Software/ Version	Notes
6A	42	21	2:1	Wi-Fi 30–50 Mbps/stable	Mozaik offline pack pre-loaded	Mozaik 3D v.X.Y	Room with projector
6B	39	20	≈2:1	Wi-Fi 10–20 Mbps/occasional drops	70% of content pre-downloaded	Mozaik 3D v.X.Y	Bring backup hotspot
7A	41	21	2:1	Wi-Fi 30–50 Mbps/stable	Full offline pack	Mozaik 3D v.X.Y	—

Note: Where internet is unreliable, ensure all 3D assets are pre-downloaded; verify projector/cables before class.

Appendix D. Short Fidelity Checklist for AR Lesson Implementation

Table D1: Is a brief observation/self-check tool. Mark Yes/No/N.A. and add short notes where relevant

ID	Item	What to Check	Observed	Notes
D1	Device preparation	Batteries ≥80%; correct 3D modules installed/offline.		
D2	Seating and roles	Pairs at 1 device; “driver” and “navigator” roles assigned.		
D3	P1 Engage	Starter activity elicits predictions relevant to topic.		
D4	P2 Explore 3D	Students manipulate 3D models; teacher prompts probing questions.		
D5	P3 Explain	Teacher references core multimedia principles during explanations.		
D6	P4 Practice	Paired/group task produces an intermediate product (worksheet/chart).		
D7	P5 Exit	Exit ticket or short quiz collected as evidence.		
D8	Classroom management	Clear signals; on-task time; and quick troubleshooting.		
D9	Inclusion and safety	All students engaged; and device handling/safety observed.		
D10	Assessment linkage	Artifacts stored/photographed per plan.		
D11	Curriculum fit	AR content aligns with intended outcomes; no extraneous load.		
D12	Post-lesson reflection	Teacher logs brief reflection for iteration.		

Observed code: ☐ Yes ☐ No ☐ N.A.