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# The Development of STEAM-Based Augmented Reality (AR) Instructional Material Model to Enhance 21st-Century Assessment Competencies for Junior High School Students

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**Abstract**
This study aims to develop and evaluate a STEAM-based Augmented Reality (AR) instructional material model for improving junior high school students' 21st-century skills in solid geometry learning. The study employed a modified Research and Development model adapted from Borg and Gall, consisting of preliminary study and needs analysis, product design, expert validation, revision, limited trial, and large-scale field testing. The participants were 75 eighth-grade students. Data were collected using expert validation sheets, student response questionnaires, and 21st-century skills tests covering critical thinking, creativity, collaboration, and communication. The data were analyzed using quantitative descriptive statistics, normalized gain (N-Gain), and an independent-sample t-test. The results showed that the developed model achieved a mean expert validation score of 4.49, indicating a very valid category. The limited trial involving 15 students produced an N-Gain score of 0.46, categorized as moderate. The large-scale trial showed that the experimental class using the AR-STEAM model improved from a pretest score of 63.2 to a posttest score of 86.7, with an N-Gain of 0.63, whereas the control class improved from 62.9 to 72.4, with an N-Gain of 0.26. The t-test showed a significance value of 0.000 ($p < 0.05$), indicating a significant difference between the experimental and control classes. These findings demonstrate that the AR-STEAM model is valid and effective for enhancing students' 21st-century skills through interactive three-dimensional visualization, project-based learning, contextual problem solving, and competency-oriented assessment.

**Keywords:** Augmented Reality; Mathematics Learning; Solid Geometry; STEAM; 21st-Century Skills

## INTRODUCTION

Solid geometry is a central topic in junior high school mathematics because it requires learners to connect visual representation, spatial reasoning, measurement, and problem solving. In classroom practice, however, many students still experience difficulty in interpreting three-dimensional objects from two-dimensional textbook images, identifying relationships among vertices, edges, faces, and nets, and transferring geometric concepts to contextual problems. This difficulty may reduce conceptual understanding and limit students' opportunities to develop higher-order thinking. Therefore, geometry instruction requires learning resources that are able to transform abstract spatial ideas into concrete, manipulable, and meaningful representations.

The rapid development of digital technology has opened new possibilities for designing mathematics learning environments that are more interactive and learner-centered. Augmented Reality (AR) is one of the promising technologies because it can overlay digital objects onto real environments and allow students to observe, rotate, and manipulate virtual three-dimensional objects in real time. Previous studies have shown that AR can support learning gains, spatial visualization, motivation, and memory retention because it provides a bridge between symbolic mathematical concepts and direct visual experience (Garzón & Acevedo, 2019; Gargrish et al., 2021; Rohendi & Wihardi, 2020; Sarkar et al., 2020). In geometry learning, this affordance is particularly important because students need to construct mental images and understand relationships among spatial elements.

Although AR has strong potential, the use of technology alone is not sufficient to guarantee meaningful learning. A digital medium should be embedded in an instructional approach that promotes inquiry, collaboration, creativity, and reflection. The STEAM approach, which integrates science, technology, engineering, art, and mathematics, provides a relevant pedagogical framework because it encourages students to solve contextual problems, design products, communicate ideas, and connect mathematical knowledge with real-life applications. Studies on STEAM and project-based learning indicate that interdisciplinary tasks can foster critical thinking, creativity, collaboration, communication, and problem-solving skills when learning activities are intentionally designed and assessed (Jesionkowska et al., 2020; Lavicza et al., 2022; Oanh & Dang, 2025; Rukayah et al., 2022).

The demand for 21st-century learning also requires assessment practices that move beyond the measurement of factual recall. Students need opportunities to demonstrate critical thinking, creativity, collaboration, and communication, commonly known as the 4C competencies. These competencies are increasingly emphasized in contemporary education because they support adaptability, problem solving, and participation in digital and knowledge-based societies (OECD, 2019; Thornhill-Miller et al., 2023). Therefore, innovative mathematics learning should not only provide interactive media but should also integrate learning activities and assessment instruments that are aligned with the development of these competencies.

Previous studies have generally examined AR as a learning medium or STEAM as a pedagogical approach in separate ways. Research on AR in geometry has demonstrated positive effects on visualization and problem-solving ability, whereas research on STEAM has highlighted the value of interdisciplinary projects and active learning (Ibáñez & Delgado-Kloos, 2018; Nindiasari et al., 2024; Rohendi et al., 2025). However, fewer studies have systematically developed an integrated instructional material model that combines AR-based 3D visualization, STEAM-oriented project activities, and 4C-based assessment within a single learning system for junior high school solid geometry. This gap indicates the need for a more comprehensive model that is not limited to media development but also addresses instructional design and competency-based assessment.

Based on this background, this study develops a STEAM-based AR instructional material model for solid geometry learning. The objectives of this study are to develop the model, examine its validity and implementation feasibility, and test its effectiveness in improving students' 21st-century skills. The novelty of this study lies in the integration of three components: AR technology as an interactive visualization tool, STEAM as a project-based and interdisciplinary learning approach, and 4C-oriented assessment as an instrument for measuring 21st-century skills. Through this integration, the developed model is expected to contribute to mathematics learning innovation that is relevant to digital-era education and suitable for junior high school students.

## METHODS

This study used a Research and Development (R&D) design adapted from the Borg and Gall development framework. The original stages were modified to suit classroom-based instructional product development and consisted of six stages: preliminary study and needs analysis, product design, expert validation, product revision, limited field testing, and large-scale field testing. This design was selected because the study aimed not only to evaluate learning outcomes but also to produce an instructional material model that had been validated and revised through systematic development procedures.

The product developed in this study was a STEAM-based AR instructional material model for solid geometry. The model consisted of AR-based visual objects, student learning activities, project-based STEAM tasks, and assessment instruments for 21st-century skills. The AR component was designed to help students observe and manipulate three-dimensional representations of solid geometry objects. The STEAM component guided students to analyze contextual problems, design solutions, construct products or representations, and communicate findings. The assessment component measured critical thinking, creativity, collaboration, and communication during the learning process and through task performance.

The research participants were 75 eighth-grade students from a junior high school. The limited trial involved 15 students and was conducted using a one-group pretest-posttest design to obtain preliminary information about product implementation and initial learning improvement. The large-scale field trial involved 60 students and used a quasi-experimental nonequivalent control group design. Students in the experimental class learned using the AR-STEAM model, whereas students in the control class learned through conventional instruction. This design made it possible to compare learning improvement between the two classes while maintaining the natural classroom setting.

Three instruments were used in this study. First, expert validation sheets were used to assess content feasibility, media feasibility, STEAM integration, and alignment of the 4C assessment instruments. Second, student response questionnaires were used to evaluate implementation feasibility from the learner perspective. Third, 21st-century skills tests and performance indicators were used to measure students' critical thinking, creativity, collaboration, and communication. The validation score was interpreted using a five-point scale, where higher scores indicated stronger product feasibility.

The data were analyzed using quantitative descriptive statistics, N-Gain analysis, and an independent-sample t-test. Expert validation data were summarized using mean scores and interpreted according to validity categories. Learning improvement was calculated using the normalized gain formula, namely the difference between posttest and pretest scores divided by the difference between the maximum score and pretest score. N-Gain scores were interpreted as low, moderate, or high improvement. The independent-sample t-test was used to determine whether the learning outcomes of the experimental and control classes differed significantly at the 0.05 significance level.

## RESULT AND DISCUSSION

### Product validation

**Table 1.** Expert validation result of the AR-STEAM instructional material model

| Aspect | Mean score | Category | Interpretation |
|---|---|---|---|
| Overall expert validation | 4.49 | Very valid | The model is feasible for implementation after minor revision. |

The expert validation results show that the STEAM-based AR instructional material model reached a mean score of 4.49. This score indicates that the product belongs to the very valid category and is feasible for implementation after minor revision. The validation covered content relevance, media design, instructional coherence, STEAM integration, and alignment between learning activities and 21st-century skills assessment. This result indicates that the model has adequate theoretical and practical foundations as an instructional product for solid geometry learning.

### Limited trial

**Table 2.** Limited trial result

| Participants | Design | N-Gain | Category |
|---|---|---|---|
| 15 students | One-group pretest-posttest | 0.46 | Moderate |

The limited trial was conducted with 15 students to examine the initial implementation of the product and its potential to improve students' 21st-century skills. The result showed an N-Gain score of 0.46, categorized as moderate. This finding suggests that AR-assisted visualization and STEAM-based tasks can help students understand geometric concepts more effectively than learning that relies only on verbal explanation or static images. During this phase, the model also provided opportunities for product revision before the large-scale trial.

### Large-scale field test

**Table 3.** Comparison of pretest, posttest, and N-Gain scores

| Class | Learning model | Pretest | Posttest | N-Gain/category |
|---|---|---|---|---|
| Experimental | AR-STEAM | 63.2 | 86.7 | 0.63 / moderate-high |
| Control | Conventional | 62.9 | 72.4 | 0.26 / low |

**Table 4.** Independent-sample t-test result

| Comparison | Significance value | Criterion | Decision |
|---|---|---|---|
| Experimental vs. control class | 0.000 | $p < 0.05$ | Significant difference |

The large-scale field test showed a stronger improvement in the experimental class than in the control class. Students who learned using the AR-STEAM model improved from a pretest score of 63.2 to a posttest score of 86.7, producing an N-Gain of 0.63. In contrast, students in the conventional class improved from 62.9 to 72.4, producing an N-Gain of 0.26. The t-test result showed a significance value of 0.000, which is below 0.05. Therefore, the improvement in the experimental class was statistically different from that of the control class.

### Discussion

The effectiveness of the model can be explained by the complementary role of AR visualization, STEAM activities, and 4C-oriented assessment. AR helped students convert abstract spatial concepts into concrete learning experiences. Students could observe the structure of three-dimensional objects, rotate visual models, and connect visual representations with mathematical formulas. This supports the cognitive theory of multimedia learning, which emphasizes the importance of integrating verbal and visual information to reduce abstraction and strengthen conceptual processing (Mayer, 2024). The finding is also consistent with previous AR studies showing that immersive and interactive visualization can support geometry learning, representational fluency, and spatial understanding (Gargrish et al., 2021; Li et al., 2022; Sarkar et al., 2020).

The STEAM component also contributed to learning improvement because students were not only asked to memorize formulas but also to investigate problems, design representations, and present solutions. The project-based nature of STEAM learning encouraged students to collaborate, communicate ideas, and use creativity in solving contextual geometry tasks. This finding supports previous studies reporting that STEAM-based and project-based learning can strengthen critical thinking, creativity, problem solving, and collaboration when learning tasks are interdisciplinary and authentic (Lavicza et al., 2022; Oanh & Dang, 2025; Rahmawati et al., 2020; Setyarto et al., 2020).

Compared with earlier studies that focused mainly on the development of AR media, the present study offers a broader instructional contribution. It combines media, pedagogy, and assessment in one integrated model. Nindiasari et al. (2024) demonstrated the usefulness of AR with a STEAM approach for geometry problem solving, while Rohendi et al. (2025) emphasized the role of AR in increasing student interactivity and responses in geometry learning. The present study extends these contributions by positioning 4C assessment as an inseparable element of the instructional model. As a result, the model does not only improve posttest scores but also provides a structured mechanism for observing and assessing students' critical thinking, creativity, collaboration, and communication.

The findings also indicate that technology integration should be accompanied by careful instructional design. AR offers strong visualization support, but learning improvement depends on how students are guided to use the visualization for reasoning, inquiry, and communication. The moderate-to-high N-Gain in the experimental class indicates that AR becomes more meaningful when embedded in STEAM tasks and supported by assessment indicators. Therefore, the developed model can be considered an effective learning innovation for solid geometry at the junior high school level. Nevertheless, the study is limited to one topic and a relatively restricted sample. Further research should test the model across different mathematical topics, schools, and learner characteristics, as well as examine long-term retention and the sustainability of students' 21st-century skills.

## CONCLUSION

This study concludes that the STEAM-based Augmented Reality instructional material model for solid geometry was successfully developed through modified Research and Development stages and achieved a very valid expert validation score of 4.49. The limited trial produced an N-Gain of 0.46, indicating moderate improvement, while the large-scale trial showed that the experimental class achieved a higher N-Gain of 0.63 compared with 0.26 in the control class. The t-test result, with a significance value of $0.000 < 0.05$, confirms a significant difference between students who learned using the AR-STEAM model and those who learned through conventional instruction. These results demonstrate that the model is effective in improving students' 21st-century skills, particularly critical thinking, creativity, collaboration, and communication, because it integrates interactive 3D visualization, STEAM-based project activities, contextual problem solving, and competency-oriented assessment. The model is therefore recommended as an innovative instructional alternative for junior high school mathematics learning, especially in solid geometry. Future studies should expand implementation to other mathematical topics, involve more schools, and explore the integration of adaptive technologies such as artificial intelligence to strengthen personalized learning and assessment.

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