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Exploring Junior High School Students' External Representations in Solving Solid Geometry Problems: A Descriptive Qualitative Study

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ABSTRACT

External representation is essential in mathematics learning because it enables students to express and operationalize abstract ideas. However, many junior high school students still struggle to coordinate visual, mathematical, and verbal representations when solving solid geometry problems. This study aims to explore how students demonstrate external representations in solving solid geometry tasks by analyzing their pretest responses. A descriptive qualitative method was used involving nine students who completed a pretest, from which three were purposively selected to represent high, medium, and low levels of external representation ability. Data were collected using a test instrument based on indicators of visual, mathematical, and verbal representations. The results show that high-performing students can consistently produce accurate visualizations, mathematical expressions, and written explanations, while medium-performing students demonstrate inconsistent and partial representations. Low-performing students encounter major difficulties in generating meaningful representations. The findings suggest that teachers should strengthen geometry instruction by promoting the balanced use of visual, mathematical, and verbal representations to support students' conceptual understanding.

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1. INTRODUCTION

External representation plays a central role in mathematics learning because it enables students to express, communicate, and operate on abstract ideas. According to Duval [1], representation is an essential component of mathematical thinking, as conceptual understanding cannot occur without it. In this study, external representation refers to three forms commonly emphasized in mathematics education: visual, mathematical, and verbal [2], [3], which together function as a bridge connecting abstract concepts with students' concrete understanding.

Solid geometry is particularly relevant for examining external representations because it demands high levels of spatial reasoning and coordination between visual and symbolic forms. Duval [1] notes that the greatest cognitive difficulty in geometry is converting between a 3D visual representation and its mathematical expression. Kirsh [4] further explains that working with spatial information increases cognitive load, making external representations essential for supporting problem solving. Previous studies on Indonesia also show that students often struggle to visualize geometric objects accurately and to express their reasoning verbally or symbolically [3], [5]. Therefore, solid geometry provides an ideal context for identifying representational challenges that naturally arise in students' mathematical thinking. To clarify the position of the three types of external representations in this study, the following conceptual framework is presented in Figure 1.

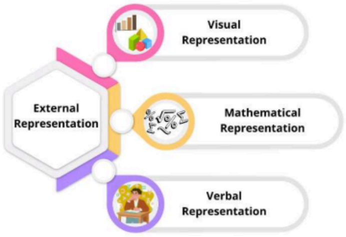


Figure 1. Conceptual Framework of External Representations

A pretest plays a strategic role in identifying students' representational tendencies. Through a pretest, researchers obtain an authentic picture of how students naturally construct visual, mathematical, and verbal representations when solving problems. The results of this pretest can serve as a basis for mapping students' external representation abilities and determining more targeted learning strategies [6], [7]. Thus, a pretest not only functions as an evaluation tool but also as an exploratory instrument rich with information about students' mathematical thinking processes.

Several studies have provided important insights regarding external representation in mathematics education. Research highlights the importance of coordinating internal and external representations to support spatial reasoning [4], the benefits of visual representation in strengthening geometric understanding [8], and the tendency of Indonesian students to rely heavily on symbolic forms while remaining weak in visual and verbal expression [9]. Other studies emphasize that providing diverse representation opportunities can enhance flexibility in problem solving [10], and project-based learning (PjBL) has been shown to strengthen students' representational and conceptual understanding in various mathematical topics [11], [12], [13].

However, despite the growing literature, few studies have examined students' external representations by analyzing their detailed written responses to solid geometry pretest items. Much of the existing work focuses on instructional interventions rather than diagnostic exploration prior to intervention. This creates a gap: little is known about how external representations spontaneously emerge in students' natural problem-solving processes, especially across different ability levels (high, medium, low).

Therefore, this study explicitly explores the patterns and quality of junior high school students' external representations in solving solid geometry problems, based on an analysis of their pretest answers. The study aims to identify differences in visual, mathematical, and verbal representations across performance levels and to provide baseline insights for designing learning that aligns with students' representational needs.

2. METHOD

This study employed a descriptive qualitative approach, as its main objective is to explore how students display external representations when solving solid geometry problems. This approach was chosen because descriptive qualitative methods allow researchers to describe phenomena in depth based on data obtained without manipulating variables [14].

A total of nine ninth-grade junior high school students participated in a pretest administered prior to the intervention phase. From these nine students, three were purposively selected to represent high, medium, and low levels of external representation ability. The purposive sampling ensured variation in representational quality, allowing the analysis to highlight distinct characteristics across performance categories. Data were collected through a pretest consisting of three solid geometry problems, each designed to elicit indicators of visual, mathematical expression, and verbal representations, resulting in a total of seven indicators being assessed. These indicators were developed with reference to external representation frameworks proposed by Duval [1] and Rangkuti [2].

The research instrument consisted of an external representation test accompanied by a scoring rubric using a 0–4 scale. Both the test items and the scoring rubric underwent expert validation conducted by two mathematics education specialists, who assessed the clarity, relevance, and alignment of the indicators with the intended constructs. Feedback from the validators led to the refinement of item wording, improvement of diagram clarity, and adjustments to rubric descriptors to ensure construct validity. In the broader context of mathematical communication, previous studies have shown that structured tasks such as problem-based learning and project-based learning can strengthen students' written explanations and symbolic representations [15], [16]. A complete scoring rubric used in this study is presented in Table 1 to improve transparency and consistency.

Table 1. Scoring Rubric for External Representation Ability

External Representation Ability Indicators	Response	Score
Visual representation (graphs, diagrams, tables, images)	Do not create any images, graphs, or tables at all.	0
	Creating images/diagrams that are incomplete or inappropriate; illegible	1
	The image or table has been created, but is not neat or accurate.	2
	The images and tables are clear and support problem-solving.	3
	Complete, neat, accurate, and systematically used images or tables to complete the project	4
Mathematical expressions (models, formulas, patterns, equations)	Not writing down mathematical expressions at all	0
	Writing down mathematical expressions that are highly incorrect or irrelevant	1
	Formulating equations or patterns, but they are not yet accurate or complete	2
	Developing mathematical models or expressions that are sufficiently accurate and can be used to solve problems	3
	Developing mathematical expressions or models that are correct, complete, and highly supportive of the project's problem-solving	4
Verbal representation (words/written text)	There is no explanation or written description whatsoever.	0
	Explanations that are incoherent, illogical, or merely copied information	1
	Explaining part of the process in writing, but it is unclear or illogical	2
	The explanation is quite comprehensive, logical, and uses mathematical terms correctly.	3
	Explaining ideas or processes very clearly, logically, coherently, and accurately in mathematical and communicative terms	4

The overall research procedure followed a structured sequence of steps. To provide a clear overview of these stages, the complete research flow is summarized in Figure 2.

Figure 2. Research Procedure Flowchart

Figure 2 provides an overview of the study's progression from the preparation stage to the analysis of students' work. The diagram helps show that each step in the process has a clear purpose and is connected to the next one. The validation stage ensures that the instrument is appropriate for measuring students' external representations, while the pretest provides the initial data needed for analysis. The selection of three students also becomes more transparent, as it is shown as part of the flow rather than a separate decision. Finally, the analysis stage highlights how students' answers were examined to identify different representational tendencies. Through this flow, readers can more easily understand how the research was conducted and how the findings were produced.

Data analysis was conducted using qualitative content analysis techniques [17], [18]. The analysis followed three core stages as proposed by Miles, Huberman, and Saldaña [19]. First, data reduction was carried out by categorizing students' written responses according to the seven external representation indicators. Second, data display was conducted using tables, matrices, and selected excerpts of student work to present representational patterns clearly. Finally, drawing conclusions involved comparing representational profiles across the three students to identify similarities, differences, and emerging themes regarding the quality of external representation in geometry problem-solving.

To ensure trustworthiness, this study applied the criteria of credibility, dependability, confirmability, and transferability as suggested in qualitative content analysis frameworks [18], [19]. Credibility was strengthened through expert validation of both the test instruments and the scoring rubric prior to data collection. Dependability was maintained by applying a consistent scoring and interpretation procedure to all student responses, using predetermined indicators of visual, mathematical, and verbal representations. Confirmability was supported by documenting all analytical decisions and obtaining a secondary review from a mathematics education expert to minimize researcher bias. Transferability was supported by providing comprehensive descriptions of the research setting, participant selection (nine students with three representative cases), and the test instruments used to assess external representation indicators, enabling readers to judge the applicability of the findings to other contexts.

3. RESULTS AND DISCUSSION

This analysis is not only intended to describe the answers produced by students but also to capture the patterns of how external representations emerge in problem-solving situations. By examining students from different ability levels, it is possible to observe how visual, mathematical, and verbal representations interact and support or fail to support one another. Such a comparison enables a deeper examination of the strengths and weaknesses of each student profile, while also providing insight into the specific challenges encountered in developing external representation skills. Based on this framework, the following section presents the detailed analysis of the three students' answers.

3.1. Results

This study aims to explore junior high school students' external representation abilities in solving geometry problems, particularly in solid geometry. The external representations in question include visual representations, mathematical expressions, and verbal representations. The analysis was conducted on three students selected from a group of nine who took the pretest. The selection of these three students was based on achievement scores, which were grouped into high, medium, and low categories. With this selection, the study is expected to provide a more comprehensive picture of the differences in the quality of external representations among students with varying ability levels.

Table 2. Answers of S1, S5, and S2 on Problem 1

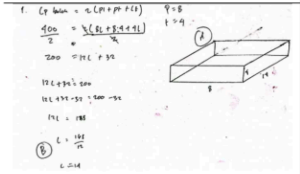
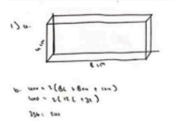
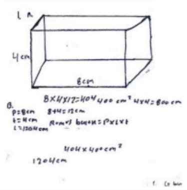
S1(High)	S5 (Medium)	S2 (Low)
		

Table 2 illustrates clear contrasts in how the three students engaged with the visual and mathematical expression indicators in Problem 1. S1 produced a proportional and accurate diagram of the rectangular prism and used it strategically as a cognitive tool to organize spatial information before transitioning to symbolic calculations. In contrast, S5 generated a sketch that was correct in form but imprecise in scale, revealing that the visual representation served more as an ornament than a functional aid for reasoning. S2 did not provide any visual representation, limiting his ability to construct a meaningful understanding of the spatial structure. These differences carried over into the mathematical expression component: S1 wrote complete and relevant formulas, S5 attempted to do so but made substitution errors, and S2 did not produce any meaningful symbolic work. Overall, the table highlights distinct patterns of representational thinking, with S1 effectively coordinating visual and symbolic forms, S5 displaying a fragmented use of representation, and S2 showing minimal engagement with both indicators.

Table 3. Answers of S1, S5, and S2 on Problem 2

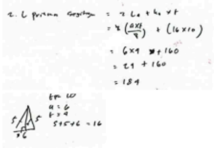
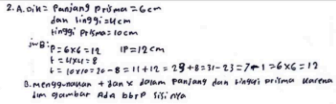
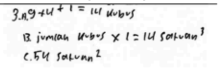
S1(High)	S5 (Medium)	S2 (Low)
		 2. A. Dik = Panjang prisma = 6cm dan tinggi = 4cm tinggi prisma = 10cm jwB: P = 6×6 = 12 IP = 12cm t = 4×4 = 8 t = 10×10 = 20 − 8 = 11 + 12 = 29 + 8 = 31 − 23 = 7 − 1 = 6×6 = 12 B. menggunakan + dan × dalam panjang dan tinggi prisma karena dim gambar Ada bbrp sisi nya

Table 3 summarizes the responses to Problem 2, which required students to apply mathematical expressions and articulate their reasoning verbally. S1 demonstrated strong coordination between symbolic and verbal representations by writing the correct formula for the surface area of a triangular prism and explaining his steps coherently with appropriate mathematical language. In contrast, S5's symbolic representation was incomplete, and his verbal explanation was brief and disconnected, indicating a fragmented approach in which symbols and reasoning were not integrated into a coherent problem-solving strategy. S2 did not provide relevant formulas or explanations, showing that he lacked representational strategies for both conceptual understanding and communication. The table thus underscores widening representational gaps across performance levels: S1's explanations reflect conceptual clarity, S5 exhibits partial but unstable understanding, and S2 demonstrates substantive difficulty in expressing geometric ideas through either symbolic or verbal forms.

Table 4. Answers of S1, S5, and S2 on Problem 3

S1(Tinggi)	S5 (Sedang)	S2 (Rendah)
 c $2(pl + pt + lt)$ $6\times5 + 6\times4 + 5\times4$ $30 + 24 + 20$ $54 + 20$ $= 74$		 3.A. $9 + 4 + 1 = 14$ kubus B. jumlah kubus $\times 1 = 14$ satuan^3 C. 54 satuan^2

As shown in Table 4, the three students' performance on Problem 3, focusing entirely on mathematical expression indicators, reveals consistent patterns that align with their overall representational profiles. S1 formulated correct mathematical models for counting unit cubes, calculating volume, and determining surface area, indicating strong procedural fluency and conceptual grounding. S5 attempted to construct mathematical expressions but frequently made operational and substitution errors, suggesting partial comprehension without the ability to translate concepts into stable symbolic procedures. S2 left several parts blank and did not generate analyzable mathematical work, reflecting significant challenges in symbolic representation. These patterns reinforce that S1 fully met all indicators, S5 met them only partially with notable inconsistencies, and S2 did not meet the mathematical expression indicators. The table thus highlights progressively diminishing representational capacity, from strategic and accurate use of symbols by S1 to almost complete absence of symbolic reasoning by S2.

Overall, the results demonstrate that S1 employed external representations strategically as tools for thinking, while S5 used them in a fragmented way with limited integration, and S2 seldom used external representations, making his reasoning process difficult to trace. These patterns underscore the crucial role of external representation in facilitating conceptual understanding in solid geometry.

Table 5. Overall Analysis of S1, S5, and S2

Student Category	External Representation Ability	Implication for Teaching
High (S1)	S1 demonstrated strong coordination across all three forms of external representation. Visual diagrams were accurate and used strategically; mathematical expressions were complete and conceptually grounded; verbal explanations were coherent and aligned with symbolic procedures.	Provide advanced tasks that integrate multiple representation forms and encourage students like S1 to articulate reasoning more explicitly to support peer learning.
Medium (S5)	S5 used all representation forms but inconsistently. Visuals lacked precision, symbolic expressions contained substitution or operational errors, and verbal explanations were brief and fragmented. Representations did not mutually reinforce one another.	Offer guided scaffolding, such as partially completed diagrams or structured templates for symbolic reasoning, to help students connect visual, symbolic, and verbal elements.
Low (S2)	S2 rarely used external representations. Visual diagrams were absent, symbolic expressions were minimal, and verbal explanations were not provided. Representational strategies were largely missing.	Provide targeted instruction emphasizing how to construct and use basic visual representations and symbolic models, supplemented by step-by-step verbal reasoning prompts.

Across the seven indicators assessed in the external representation framework, S1 fulfilled all indicators: visual representation (1a), mathematical expression (1b, 2a, 3a–3c), and verbal explanation (2b). S5 demonstrated partial fulfillment of the indicators; he produced visual and symbolic representations, but with inconsistencies in accuracy, completeness, and conceptual alignment. Additionally, his verbal explanations were underdeveloped. S2 showed minimal fulfillment, meeting only a small number of the indicators. He omitted visual representation, rarely produced symbolic expressions, and provided no verbal explanation across the three problems. These differences reveal qualitative distinctions in how each student engages with external representations as tools for conceptualizing and solving geometric problems.

3.2. Discussion

The findings of this study provide a deeper understanding of the variation in external representation abilities among junior high school students in solving geometry problems. The analysis reveals that high-category students (S1) consistently presented various forms of external representation in a mutually supportive manner. Neat and accurate drawings, precise mathematical calculations, and coherent written explanations indicate integration between visual, mathematical, and verbal representations. This pattern aligns with Duval's theory of semiotic representation registers, which states that mathematical understanding depends on students' ability to coordinate and convert between different representation systems [1]. S1's performance also reflects Kirsh's notion of "thinking with external representations," where diagrams and symbolic expressions function as cognitive tools that extend reasoning rather than merely illustrate it [4].

In contrast, medium-category students (S5) showed attempts to use different forms of representation, but the quality was inconsistent. Calculation errors, incorrect substitutions, and incoherent verbal explanations indicated a gap between their conceptual understanding and the external representations they produced. This finding is consistent with [2], who stated that students at the medium level often experience difficulties in simultaneously linking visual, mathematical, and verbal representations. This phenomenon also supports the work of [20], which emphasized the importance of transforming internal representations (mental understanding) into external representations (such as drawings, symbols, and words). The inability to make this transformation led medium-category students to produce partial representations that did not adequately support problem-solving. Thus, S5's representational output illustrates a partial or unstable coordination between representation registers, resulting in fragmented rather than functional representations.

Furthermore, PjBL has been proven to enhance mathematical problem-solving abilities among vocational high school students [21] and enrich learning experiences through the use of digital media, such as Mentimeter in geometry lessons [22]. The use of GeoGebra within the PjBL framework also improves the mathematical reasoning skills of senior high school students [23]. Moreover, the integration of advanced technologies such as Augmented Reality in PjBL-based geometry learning has been shown to strengthen students' visual representations [24].

Low-category students (S2) demonstrated the greatest challenges. Their answers were not only incomplete but also often illogical, with many items left blank. The absence of drawings, formulas, and written explanations indicates that these students had not yet mastered the basic skills of using external representations. This finding is consistent with [3], which revealed that low-ability students often struggle to write mathematical expressions or produce accurate visual representations, thereby preventing them from effectively communicating their understanding. This suggests that without structured scaffolding, students in the low category may remain at the level of isolated or non-representational thinking, unable to externalize their internal reasoning in any productive form.

Compared with previous research, which generally investigates students' representational improvements after instructional interventions such as Project-Based Learning or digital tools [21], [22], [23], [24], this study offers a distinct contribution by examining representation patterns prior to instruction, using pretest-based analysis. This baseline perspective offers insight into the natural tendencies and challenges that students bring to geometry learning before any pedagogical support is introduced. Such findings provide an empirical map of students' representational readiness, a gap that has been underexplored in earlier studies.

Overall, this study confirms the crucial role of external representation in mathematics learning, particularly in the context of geometry. Differences in the quality of external representations among high-, medium-, and low-category students demonstrate that representation is not merely a technical skill, but rather a bridge between conceptual understanding and mathematical communication. This is consistent with [4], which highlights that external representations can enhance students' cognitive capacity in addressing complex problems. Based on these findings, teachers could scaffold representational thinking by guiding students to translate between diagrams and symbolic equations, such as through multi-representation worksheets, structured verbal explanation prompts, or dynamic visualizations using tools like GeoGebra. Such strategies can strengthen students' ability to coordinate visual, mathematical, and verbal representations in an integrated manner.

This study has several limitations. The number of participants was small (nine students in the pretest and three selected for in-depth analysis), which limited the generalizability of the findings. Moreover, the study provides only a single-time snapshot of students' representation ability. Future research could expand the sample size, employ longitudinal designs to track representational development, or integrate digital technologies to explore how external representations evolve when students engage with interactive media.

4. CONCLUSION

This study reveals notable variation in junior high school students' external representation abilities when solving solid geometry problems, underscoring differences in how learners at various performance levels coordinate visual, mathematical, and verbal forms. The findings indicate the need for instructional practices that deliberately scaffold representational fluency, such as supporting students in translating between diagrams and symbolic equations or using structured multi-representation worksheets. This study is limited by its small sample and single-site context, which may constrain generalizability. Future research should design and test targeted instructional interventions, particularly those integrating digital visualization tools, to strengthen students' representational competencies. This study serves as an initial baseline for advancing multi-representation pedagogy in mathematics education.

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