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Students' mathematical problem-solving processes based on learning styles: An APOS theory and Newman's error analysis perspective

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Abstract

Mathematical problem-solving is a core competency in classroom contexts, yet many students experience difficulties when dealing with contextual tasks. This study aims to analyze students' mathematical problem-solving processes based on learning styles using APOS theory and Newman's Error Analysis (NEA). A qualitative case study was conducted in an Indonesian senior high school involving 35 eleventh-grade students (N = 35), with three students selected for in-depth analysis. Data were collected through a learning style questionnaire, problem-solving tests, and semi-structured interviews, and analyzed thematically by integrating APOS stages with NEA. The findings reveal varied cognitive pathways across learning styles rather than fixed error patterns. Visual students tended to construct accurate representations but still encountered comprehension difficulties. Auditory students articulated solution strategies clearly, although some experienced challenges in transforming problems into mathematical models. Kinesthetic students benefited from concrete supports such as diagrams, which facilitated progression toward higher APOS stages. All focal students demonstrated development toward the schema stage, indicating diverse but productive learning trajectories. These results highlight the importance of adaptive instructional strategies that align with students' learning characteristics and support structured progression in mathematical understanding.

Keywords:
APOS theory, Learning styles, Mathematical problem-solving processes, NEA

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1. INTRODUCTION

Mathematical problem-solving is widely recognized as a central competency in mathematics learning, particularly in classroom contexts where students are expected to interpret, analyze, and apply concepts to contextual situations (Azizah et al., 2022; Harahap et al., 2024; Harisman et al., 2020, 2021). It is not merely a procedural skill but a foundation for critical thinking, logical reasoning, and decision-making (Riyadi et al., 2021; Widodo, 2017). International frameworks emphasize problem-solving as a key indicator of mathematical literacy (NCTM, 2000). These perspectives highlight that mathematics education should go beyond procedural fluency and support students in constructing meaningful understanding through engagement with non-routine problems. In addition, problem-solving activities are increasingly viewed as a means to develop students' ability to connect mathematical ideas across topics, fostering flexible thinking and deeper conceptual understanding in diverse learning situations (Julita, 2017; Meryansumayeka et al., 2021).

In Indonesia, this orientation is reflected in the Merdeka Curriculum, which supports student-centered approaches such as project-based learning and authentic assessment to foster real-world problem-solving abilities (Wahyudin et al., 2024). However, empirical evidence suggests that students still encounter difficulties when working with contextual and non-routine problems, particularly those requiring reasoning, modeling, and interpretation (Afgani & Paradesa, 2021; Meryansumayeka et al., 2021). Students often struggle to identify relevant information, represent problems mathematically, and select appropriate strategies (Harisman et al., 2020; Jitendra et al., 2017; Purnomo et al., 2024). These challenges indicate that students' mathematical problem-solving processes remain inconsistent and require further investigation (Angkotasan et al., 2024; Harisman et al., 2021; Sari et al., 2023). Such inconsistencies are often reflected in students' inability to transfer previously learned concepts to new problem contexts, suggesting gaps in both conceptual understanding and strategic competence.

Such difficulties can be understood from multiple perspectives. Cognitively, students may experience obstacles in translating verbal information into mathematical representations, which can lead to incomplete or incorrect solution processes (Angkotasan et al., 2024; Julita, 2017). Psychologically, factors such as mathematics anxiety, low self-confidence, and limited persistence may also influence students' engagement and performance (Brewster & Miller, 2023; Muhtadi et al., 2022; Surya et al., 2017; Yurt, 2022). Students who experience high levels of anxiety often give up prematurely, avoid attempting alternative strategies, or fail to check their work thoroughly (Mitchell & George, 2022).

When students feel afraid or unsure about the answers they provide, they tend to give up before attempting to solve the problem thoroughly (Destiniar et al., 2024; Yurt, 2022). These findings suggest that understanding students' mathematical problem-solving processes requires an approach that considers both cognitive development and individual differences (Harisman et al., 2020, 2021). Furthermore, linguistic challenges, such as difficulties in interpreting problem statements or mathematical language, may also contribute to misunderstandings, particularly in complex or multi-step problems.

To examine students' cognitive development, APOS theory provides a well-established framework that conceptualizes learning as a progression through action, process, object, and schema stages (Arnawa et al., 2019; Yerizon et al., 2024). The first stage in this theory is action, which refers to mental or physical activities carried out explicitly and procedurally in solving mathematical problems. For example, adding two numbers directly with the help of simple calculations. At this stage, students follow instructions without a deep understanding of the concepts behind the procedures. The process occurs when students perform these actions internally without external assistance and begin to understand the logic or flow of the procedures. For example, students begin to realize why addition or factorization can be performed in a certain way. This process involves mental visualization and conceptual understanding.

Next, the object stage is reached when students see a process as a whole entity that can be analyzed, modified, or generalized. For example, students understand functions as rules, as well as objects that can be composed, transformed, or represented graphically and symbolically. The final stage is schema, which organizes various actions, processes, and objects that are interrelated into a single complex understanding. Students have high flexibility in mathematical thinking and are able to connect various concepts to solve problems creatively and efficiently (Arnon et al., 2014; Asiala et al., 1996). These stages describe how students transform external, procedural actions into internalized processes, reify these processes into objects of thought, and integrate them into broader conceptual schemas. Numerous studies have demonstrated the usefulness of APOS theory in analyzing the depth and structure of students' mathematical understanding (Arnawa et al., 2019; Asiala et al., 1996; Listiawati et al., 2025; Yarman et al., 2024; Yerizon et al., 2024).

In parallel, NEA offers a systematic procedure to identify errors in problem-solving, including Reading Error (RE), Comprehension Error (CE), Transformation Error (TE), Process Skill Error (PE), and Encoding Error (EE) (Newman, 1977). Rather than implying deterministic relationships, these frameworks can be used to examine how students' thinking processes and potential difficulties intersect during problem-solving (Valdez & Taganap, 2024; Wardhani & Argaswari, 2022; Yarman et al., 2025). The integration of these two frameworks allows for a more comprehensive analysis, as APOS focuses on cognitive construction while NEA highlights observable breakdowns in problem-solving performance.

In addition, students' approaches to mathematical problem-solving may vary according to their learning styles. The visual, auditory, and kinesthetic classification provides a useful lens to explore how students process information and engage with tasks (Fleming, 2001; Harisman et al., 2020). For instance, visual students may excel at diagrammatic representation but struggle with verbal instructions, while auditory students may prefer discussion but find abstract symbols challenging. Studies also suggest that mismatches between teaching approaches and students' learning preferences can contribute to misunderstanding and errors (Harisman et al., 2025; Harisman et al., 2019; Juniati & Budayasa, 2024; Rivai et al., 2023).

Meanwhile, multimodal learning, which integrates multiple sensory channels, has been found to enhance flexibility and adaptability in problem solving (Malacapay, 2019; Rijal et al., 2025). In the Indonesian context, the emphasis on differentiated instruction in the Merdeka Curriculum reinforces the relevance of incorporating students' learning styles into pedagogical design (Djatmika & Astutik, 2023; Umar et al., 2025).

Previous studies suggest that students with different learning preferences may demonstrate different strategies and tendencies when solving problems (Altun, 2019; Bosman & Schulze, 2018; Yorganci, 2018). However, these differences should be viewed as tendencies rather than fixed characteristics, and their relationship with cognitive development and error patterns requires further exploration. Understanding these variations is important for designing instructional approaches that are responsive to students' needs and that support multiple pathways toward mathematical understanding (Azizah et al., 2022; Harisman et al., 2021).

Despite the growing body of research, existing studies tend to examine APOS theory, NEA, and learning styles separately. This separation limits a more comprehensive understanding of how students' mathematical problem-solving processes develop and where potential difficulties arise. In particular, it remains unclear how learning styles may relate to students' progression across APOS stages and how this is reflected in the types of errors identified through NEA. This gap suggests the need for an integrated analytical approach that connects these perspectives. Without such integration, it is difficult to identify how instructional strategies can simultaneously address cognitive development and individual learning differences in a coherent manner.

Therefore, this study examines students' mathematical problem-solving processes by integrating APOS theory, NEA, and learning styles within a single analytical framework. The problem-solving indicators used in this study are adapted from Rahayu et al. (2023) and are operationalized in the methodology section. Specifically, this study addresses the following research questions: (1) How do students with different learning styles demonstrate mathematical problem-solving processes across APOS stages? (2) What types of errors, as identified through NEA, are observed in these processes?

By addressing these questions, this study aims to provide a more nuanced understanding of students' mathematical problem-solving processes and to offer insights for developing instructional strategies that support diverse learning needs. The research offers a multidimensional explanation that connects cognitive development, preferred modalities of learning, and sources of error. Theoretically, this contributes to the extension of APOS applications by situating it within differentiated learning contexts. Methodologically, it introduces a combined framework that can be used to analyze both cognitive processes and error patterns in greater depth. Practically, it provides teachers with evidence-based insights to design adaptive interventions that accommodate diverse learning styles, minimize common errors, and strengthen students' mathematical problem-solving competencies.

2. METHOD

This study employed a qualitative approach using an exploratory multiple-case study design. This design was selected to enable an in-depth examination of students' mathematical problem-solving processes across different learning styles within a natural classroom context (Creswell & Creswell, 2017; Yin, 2018). The study was conducted at an Indonesian public senior high school, namely *SMA Negeri 8 Padang*. Eleventh-grade students were chosen because they had been exposed to non-routine and contextual mathematical problems in the curriculum, making them appropriate participants for examining higher-order problem-solving processes.

A total of 35 students participated in the initial phase. A learning style questionnaire based on the VARK model (Visual, Auditory, Read/Write, Kinesthetic) developed by Fleming (2001) was adapted into *Bahasa Indonesia*. The adaptation process involved forward and backward translation to ensure linguistic equivalence. The instrument was reviewed by two experts in mathematics education and educational psychology to establish content validity. A pilot test was conducted with 30 students from a comparable school, yielding a Cronbach's alpha coefficient of 0.82, indicating acceptable reliability.

Based on the questionnaire results, three students were purposively selected for in-depth analysis. A dominant learning style was operationally defined as a score of at least 70% in one modality and at least 10% higher than other modalities. This selection enabled a focused exploration of variation across cases while maintaining analytical depth, consistent with multiple-case study principles (Yin, 2018).

Data were collected using three instruments: (1) the adapted VARK questionnaire, (2) a mathematical problem-solving test, and (3) semi-structured interviews. The test items were developed by the researchers in Indonesian and validated by two mathematics education experts. The following are excerpts from the questions given to the students.

> *"The garden that Aninda will create is shaped like two large circles and a small circle. The small circle has a diameter of 350 cm, while the large circle has a diameter of 400 cm. The small circle is divided into 8 equal segments. Each segment will be planted with soka flowers, white mini rombusa, lily day, and bombay silk in sequence so that the entire area of the small circle is filled with these plants. In Aninda's garden design, the area between the two circles will be planted with broad-leaved carpetgrass. If the price of broad-leaved carpetgrass is Rp 8,000.00 for a 30 cm x 30 cm size, with shipping costs of Rp 16,000.00 per square metre, determine the minimum cost for purchasing broad-leaved carpetgrass."*

Various theoretical frameworks have been developed to analyze the stages and processes of mathematical problem solving. Polya (1973) introduced the classic four-step model, namely understanding the problem, devising a plan, carrying out the plan, and reviewing the solution. More recent studies, such as those by Gravemeijer et al. (2017) and Pujiastuti et al. (2018), have expanded Polya's ideas by linking them to the design of learning trajectories in mathematics education. The operational indicators of mathematical problem-solving used in this study are presented in Table 1. Interviews were conducted in Indonesian to allow students to express their reasoning naturally, and were audio-recorded and transcribed verbatim.

Table 1. Problem solving indicators

Stages	Indicators
Reading and understanding the problem.	1. Read the questions. 2. Write down the questions correctly. 3. Explain the information provided.
Representing the problem.	1. Write problem-solving questions. 2. Represent problems through mathematical models, pictures, algebraic symbols, diagrams, graphs, and scripts.
Constructing problem-solving strategies.	1. Write and systematize the formulas applied correctly.

Stages	Indicators
	2. Write down the sequence of strategies in solving problems in order and completely using the given elements, mathematical models, and problem representations presented.
Solving problem.	1. Perform accurate mathematical calculations based on selected formulas, strategies, and representations. 2. Determine the final answer based on the question provided.
Confirming the answer.	1. State your answer based on your interpretation of the question.

Students' written responses and interview transcripts were analyzed using a combination of deductive and inductive thematic analysis. A coding framework was developed by integrating APOS stages with NEA categories. To avoid oversimplification, coding decisions were based on students' reasoning processes rather than final answers alone. For example, TE was identified when students misrepresented a problem into an incorrect mathematical model, whereas PE referred specifically to computational or procedural inaccuracies despite correct representation (Ahyan et al., 2019; Valdez & Taganap, 2024; Yarman et al., 2024; Yerizon et al., 2025). The complete coding framework used to analyze students' problem-solving processes is presented in Table 2.

Table 2. NEA coding scheme in mathematical problem-solving

Code	Operational Definition	Key Indicators in Student Work	Decision Rules	Example
RE	The student fails to correctly read or recognize key words, symbols, or numerical information in the problem.	Misreading numbers, units, or terms; skipping important information.	Code as RE only if the error originates from incorrect reading of the problem text, not misunderstanding meaning. If student reads correctly but misinterprets, code as CE.	Student reads "350 cm" as "300 cm" or ignores given diameter.
CE	The student reads the problem but does not understand what is known or what is being asked.	Incorrect identification of known/unknown variables; incomplete restatement of problem.	Code as CE when the student fails to interpret the meaning of the problem, even if reading is accurate. If representation is incorrect despite correct understanding, consider TE.	"The question asks for number of plants," instead of total cost.

Code	Operational Definition	Key Indicators in Student Work	Decision Rules	Example
TE	The student is unable to translate the problem into an appropriate mathematical model or representation.	Incorrect formula selection; wrong mathematical model; inappropriate diagram or equation.	Code as TE when the student misrepresents the problem mathematically, even if they understand the context. If representation is correct but calculation is wrong, code as PE.	Using area of rectangle instead of area of circle for garden.
PE	The student correctly represents the problem but makes errors in executing procedures or calculations.	Arithmetic mistakes; incorrect algebraic manipulation; procedural errors.	Code as PE only when the strategy and model are correct, but execution is flawed. If both model and calculation are wrong, prioritize TE.	Correct formula used, but incorrect multiplication or unit conversion.
EE	The student fails to express the final answer appropriately based on the problem requirements.	Missing conclusion; incorrect units; incomplete or ambiguous final answer.	Code as EE when the solution process is complete but the final answer is incorrectly stated, formatted, or interpreted. Do not code EE if earlier stages already failed.	Final answer given without units or not answering the question asked.

Error coding followed a hierarchical decision rule. When multiple errors appeared, the earliest error in the problem-solving process was identified as the primary error, as it influenced subsequent steps. Coding decisions were based on both written responses and interview data to ensure that classifications reflected students' reasoning processes rather than final answers.

Two independent coders analyzed the data, and discrepancies were resolved through discussion to reach agreement. The analysis followed three stages, namely data reduction, data display, and conclusion drawing (Miles et al., 2014). Data validity was ensured through source triangulation (tests and interviews) and member checking with participants to confirm the accuracy of interpretations.

3. RESULTS AND DISCUSSION

3.1. Results

The students' mathematical problem-solving processes were analyzed qualitatively based on their progression through the APOS stages, supported by descriptive numerical summaries to indicate distribution patterns. From the 35 students, seven students did not provide any response, indicating difficulties at the initial stage of problem engagement. Ten students demonstrated characteristics of the process stage, as they were able to identify relevant information such as the dimensions of the circles, the price of grass per unit, and the shipping cost per square metre, and proceeded to construct intermediate calculations.

Fifteen students reached the object stage, where they were able to coordinate multiple procedures, including calculating areas, determining the number of grass units required, and estimating total costs. Only three students demonstrated the schema stage, characterized by the ability to organize a complete and coherent sequence of problem-solving steps from interpreting the garden design to determining the final cost.

Table 3. Relationship between APOS stages and Newman error

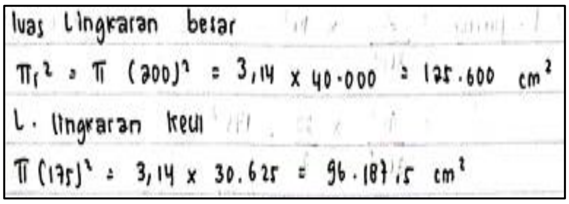
APOS Stages	Newman's Error				
	RE	CE	TE	PE	EE
Action	20%	-	-	-	-
Process	-	-	28.57%	-	-
Object	-	-	37.14%	5.71%	-
Schema	-	-	-	-	-

Table 3 presents a descriptive summary of how errors identified through Newman's error analysis were distributed across APOS stages. The percentages are calculated based on the total number of students (N = 35). The symbol "–" indicates that no instances of a particular error type were identified at the corresponding APOS stage. At the action stage, approximately 20% of students exhibited reading-related difficulties, reflected in their inability to initiate a response. At the process stage, 28.57% of students showed indications of transformation errors, particularly in representing the problem into appropriate mathematical forms. Similar tendencies were observed at the object stage, where 37.14% of students experienced difficulties in constructing correct mathematical models, while 5.71% demonstrated process skill errors related to computational inaccuracies. No encoding errors were identified in this study.

These findings should be interpreted as indicative patterns rather than causal relationships, as the analysis aims to explore how students' problem-solving processes and potential difficulties are reflected across APOS stages. The results provide a descriptive basis for understanding variations in students' thinking processes, which are further elaborated in relation to learning styles in the following section.

Visual Student (VS)

VS is able to understand the question and identify what is known and what is being asked in the question. The first step taken by VS is to determine the shape of the area to be planted with broad-leaved carpetgrass by calculating the area of each circle, as shown in Figure 1.



luas Lingkaran besar

$\pi r^2 = \pi (200)^2 = 3,14 \times 40.000 = 125.600$ cm^2

L. lingkaran kecil

$\pi (175)^2 = 3,14 \times 30.625 = 96.187,5$ cm^2

Translation:
Area of large circle:
$\pi r^2 = \pi(200)^2 = 3.14 \times 40{,}000 = 125{,}600$ cm^2
Area of small circle:
$\pi(175)^2 = 3.14 \times 30{,}625 = 96{,}187.5$ cm^2

Figure 1. Results of VS' interiorization

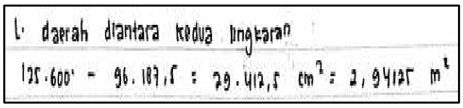
Researcher : *When calculating the areas of the large and small circles, you immediately use the formula πr^2. Can you explain why you chose that formula and how you calculated it?*

VS : *Since it is circular in shape, I used the formula for the area of a circle. For the large circle, I knew the radius was 200 cm, so I squared it and multiplied it by 3.14. I did the same for the small circle.*

Researcher : *Did the image provided help you solve this problem?*

VS : *That's very helpful, ma'am. I need to see the shape first so I can tell which fingers to use. If I just read the numbers without pictures, I get confused, ma'am.*

In this section, students calculate the areas of large and small circles using formulas. This process is still carried out procedurally and explicitly, indicating that students have only just begun to internalize actions as part of the thinking process. After that, students calculate the difference in area between two circles, as shown in Figure 2.



L. daerah diantara kedua lingkaran

$125.600 - 96.187,5 = 29.412,5$ cm^2 $= 2,94125$ m^2

Translation:
The area between the two circles:
$125{,}600 - 96{,}187.5 = 29{,}412.5$ cm^2 $= 2.94125$ m^2

Figure 2. Results of VS' coordination

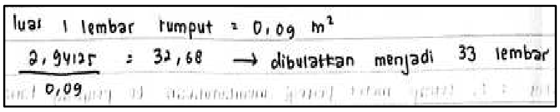
Researcher : *Once you have obtained the areas of the large and small circles, subtract the results. Why do you do that?*

VS : *Because in the picture, I see a small circle inside a large circle. So the part planted with grass is only between the two circles. That's why I calculated the difference in area, ma'am.*

Researcher : *So, you're connecting two calculations from two images?*

VS : *That's right, ma'am. I marked the outer edge and inner edge with different colors so that it is clear which parts are counted, ma'am.*

The coordination stage occurs when students connect the process of calculating the area of two circles to produce new information, namely the area of a ring-shaped area. It means that students are able to combine two calculation processes into one problem-solving goal. Figure 3 shows the process of students converting area into the number of grass sheets.



luas 1 lembar rumput = 0,09 m²

$\frac{2,94125}{0,09}$ = 32,68 → dibulatkan menjadi 33 lembar

Translation:

Area of 1 piece of grass = 0.09 m^2

$\frac{2.94125}{0.09} = 32.68 \rightarrow$ rounded up to 33 sheets

Figure 3. Results of VS' reversal

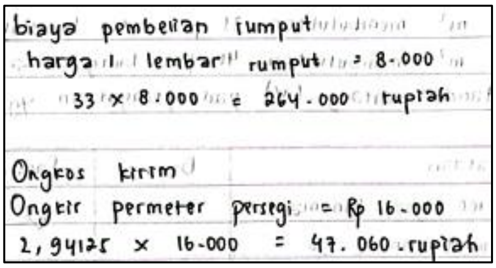
Researcher : *After obtaining the area, you divide it by 0.09 to find the number of grass sheets. Can you explain why?*

VS : *Since I saw that one sheet of grass measures 30 cm x 30 cm, I converted it to square metres and calculated that one sheet is 0.09 m². In this case, the total area is divided by the area of one sheet.*

Researcher : *Are you creating images to help?*

VS : *Yes, ma'am, I made small squares to represent the grass. Then I tried to imagine how many squares would fit in the area I had calculated earlier.*

From the excerpt above, it is evident that the students reversed the calculation process from total area to number of pieces. This is a form of reversal, whereby students perform the opposite process from total size to the smallest unit (sheets of grass). Next, the students use the area and the number of grass sheets to calculate the required cost, and understand the calculation results as a whole, as shown in Figure 4.



biaya pembelian rumput

harga 1 lembar rumput = 8.000

33 x 8.000 = 264.000 rupiah

Ongkos kirim

Ongkir permeter persegi = Rp 16.000

2,94125 x 16.000 = 47.060 rupiah

Translation:

Cost of purchasing grass:

Price of 1 piece of grass = 8,000

33 x 8,000 = 264,000 rupiah

Shipping cost:

Shipping cost per square meter = Rp 16,000

2.94125 x 16,000 = 47,060 rupiah

Figure 4. Results of VS' de-encapsulation and encapsulation

Researcher : *The area and number of sheets obtained are then used to calculate the cost. Can you explain why you do this?*

VS : *Since I consider the area to be final, now we just need to use it. I calculate how many sheets there are, then multiply that by the price. The same goes for shipping costs; I just multiply that by the total area.*

Researcher : *Do you still imagine the shape or image when calculating the cost?*

VS : *Yes, ma'am. I think the area is like a circular garden, and I filled in the small boxes. After finding out the number of boxes, I just bought the appropriate amount.*

Researcher : *You get the purchase cost = 33 x 8,000 = 264,000. In this section, are you still thinking about the previous process?*

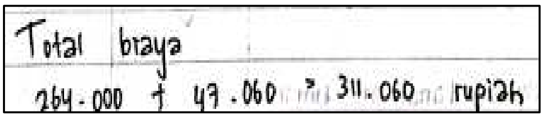
VS : *Not really, ma'am. I consider 33 to be correct, so just multiply it. For me, it is a fixed number that represents the results of the entire previous process.*

Researcher : *So you see it as a whole number?*

VS : *Yes, ma'am, like the final number from that section.*

Students utilize previously created mathematical objects (area and number of sheets) in calculating costs. Students open the created objects to be included in the subsequent process.

This demonstrates the main characteristic of de-encapsulation. Furthermore, students treat the results of previous processes as complete objects. Purchase costs and shipping costs are not recalculated but are considered part of the final process. This is a form of encapsulation where processes are condensed into ready-to-use objects. Figure 5 shows the process of students adding up the final costs and ensuring the results are correct.



Total biaya

264.000 + 47.060 = 311.060 rupiah

Translation:
Total cost:
264,000 + 47,060 = 311,060 rupiah

Figure 5. Results of VS' confirmation

Researcher : Finally, add 264,000 to 47,060 to get the total cost. How can you be sure that your answer is correct?
VS : I checked the previous calculations again, ma'am, and saw that the calculation flow was in line with the diagram and table I had created. If I can imagine the final result matching the initial form, then I am confident.
Researcher : Do you use visualization to check your answers too?
VS : Yes, ma'am, I compared the initial design with the cost estimate. Does it make sense for such a large area?

The confirmation stage is when students confirm the final result through verification and consolidation of all steps. The total cost calculation shows that students are confident that they have completed all stages correctly and confirm the final solution. Based on the excerpt above, it can be concluded that VS relies on images, sketches, and colors to understand concepts, uses visualization to connect information and verify its accuracy, and transforms verbal information into spatial forms to facilitate mathematical thinking processes. Figure 6 shows the results of the analysis of VS's problem-solving process based on the APOS theory.

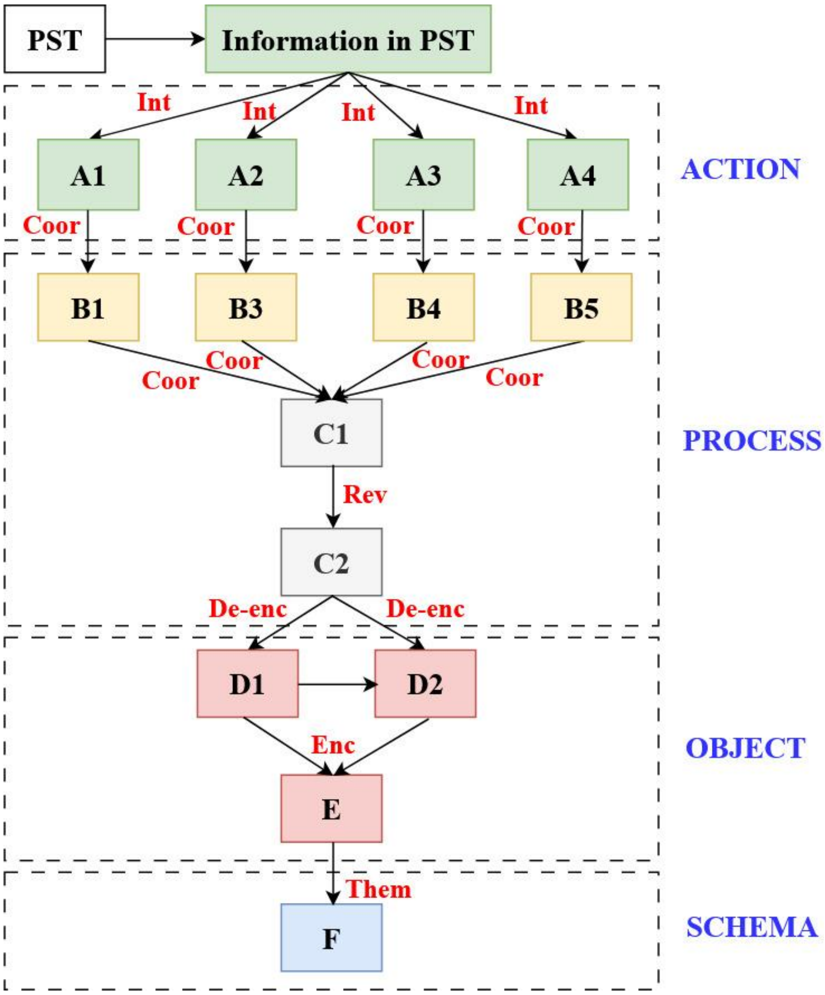


Figure 6. Analysis of VS' problem solving processes

The code description of Figure 6 about the Analysis of VS's problem-solving processes is presented in Table 4.

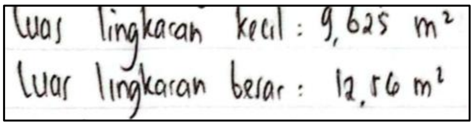
Table 4. Description of codes in Figure 6

Code	Description	Code	Description
PST	Problem Solving Test.	E	Calculating the total cost of purchasing broad-leaved carpetgrass.
A1	Identifying the size of broad-leaved carpetgrass.	F	Designing a complete sequence of steps from the shape of the garden to the cost.
A2	Identifying the price per piece of grass.	Int	Interiorization.
A3	Identifying shipping costs per m^2.	Coor	Coordination.
A4	Identifying the objective: the lowest cost for purchasing broad-leaved carpetgrass.	Rev	Reversal.
B1	Determining the radii of the large and small circles.	De-enc	De-encapsulation.

Code	Description	Code	Description
B3	Calculating the area of large and small circles.	Enc	Encapsulation.
B4	Calculating the difference in area between two circles.	Them	Thematization.
B5	Converting the unit of area of a circle from cm^2 to m^2.	🟩	Reading and understanding the problem.
C1	Determining the area of one piece of broad-leaved carpetgrass.	🟧	Representing the problem.
C2	Calculating the amount of grass clippings required.	⬜	Constructing problem-solving strategies.
D1	Multiplying the number of grass cuttings by the price per cut.	🟪	Solving problem.
D2	Multiplying the area by the shipping cost per m^2.	🟦	Confirming the answer.

Auditory Student (AS)

When given a problem-solving question, AS reads the question and identifies what is known and what is being asked. Then AS calculates the area of the large and small circles as shown in Figure 7.

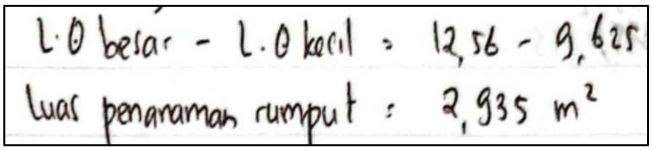

Luas lingkaran kecil : 9,625 m^2
Luar lingkaran besar : 12,56 m^2

Translation:
Area of small circle = 9.625 m^2
Area of large circle = 12.56 m^2

Figure 7. Results of AS' interiorization

Researcher	:	*When you calculate the area of large and small circles, what helps you remember the formula and work it out?*
AS	:	*I remember when my math teacher explained that 'the area of a circle is π times the radius squared.' I repeated that to myself over and over while working on the problem. I usually like to say it slowly while writing, like 3.14 times two squared.*
Researcher	:	*So, are you more comfortable hearing or saying the steps?*
AS	:	*Yes, ma'am, if I just look at the formula, sometimes I forget. But if I say it out loud, I can immediately move on to the next step.*

AS demonstrated the ability to perform the initial procedure by directly using the formula for the area of a circle. AS probably recalled the teacher's verbal instructions when explaining the formula for the area of a circle and applied it sequentially according to what they had memorized or heard before. Then AS calculated the difference between the areas of the large and small circles, as shown in Figure 8.


L.O besar - L.O kecil = 12,56 - 9,625

luas penanaman rumput = 2,935 m^2

Translation:
Area of large circle – Area of small circle = 12.56 - 9.625
Area of grass planting = 2.935 m^2

Figure 8. Results of AS' coordination

Researcher : *You subtract the areas of the two circles to get the area of the lawn. Why do you do that?*

AS : *When it was explained in class, the teacher said, 'If there are two circles, subtract the outer circle from the inner circle, and the result is the area between them.' So when I saw the numbers, I immediately remembered that sentence and knew I had to subtract.*

Researcher : *So you connect what you hear with the steps you take?*

AS : *Yes, ma'am. I remember the teacher's voice and the way they explained things, so that's what I follow. Sometimes I like to imitate their tone of voice too, so it's easier to remember.*

AS combined two separate processes (the areas of the large and small circles) to obtain the area of the lawn. AS remembered the teacher's explanation about subtracting the two areas to find the area between the two circles and then applied it. Figure 9 shows that AS converted the area into the number of grass blades.

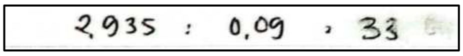

2,935 : 0,09 = 33

Figure 9. Results of AS' reversal

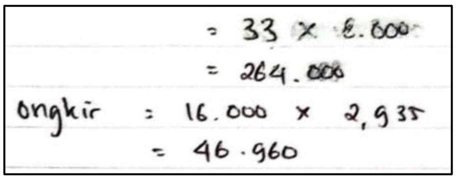
Researcher : *Once you have obtained the area, divide it by the area of one blade of grass. Why do you know you have to do that?*

AS : *Because I remember my teacher once said, 'If you want to know how many sheets there are, divide the total area by the area of one sheet.' I repeated that sentence slowly in my mind, then I started calculating.*

Researcher : *Do you often repeat sentences like that when doing problems?*

AS : *That's right, ma'am, it really helps me. If I can hear the words again, I can continue with the steps. Otherwise, I get confused, ma'am.*

AS converts from the final result (area) to the basic unit (sheet). AS tends to remember the verbal steps taken by the teacher or friends in explaining the conversion, such as total area divided by unit area per sheet. Next, AS multiplies the number of sheets of grass by the price per sheet and the area by the shipping cost per m², as shown in Figure 10.


= 33 x 8.000
= 264.000
ongkir = 16.000 x 2,935
= 46.960

Translation:
= 33 x 8,000
= 264,000
Shipping cost = 16,000 x 2.935 = 46,960

Figure 10. Results of AS' de-encapsulation and encapsulation

Researcher : *When you calculate the cost based on the number of sheets and the area, you simply multiply it by the price. Why?*

AS : *I considered those 33 sheets to be the final result of the process, ma'am. Then I remembered that the question mentioned the price per sheet. So, I immediately said to myself, 'sheets multiplied by price.' The same goes for shipping costs, just 'area multiplied by shipping costs.'*

Researcher : *Do you feel that it is a follow-up step that just needs to be implemented?*

AS : *Yes, ma'am, because I already have those numbers stored in my head. So, when it comes to the costs, I just have to recall in my mind what needs to be multiplied.*

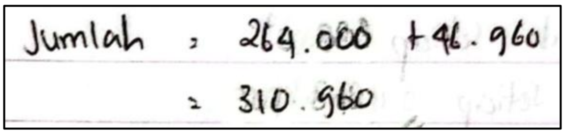
Researcher : *You can use the numbers 264,000 and 47,040 to calculate the total. Are you still thinking about the previous process?*

AS : *No, ma'am. I already consider that to be the final price. In my mind, that is the total price of the grass and the shipping costs, so I just added them together, ma'am.*

Researcher : *So, you use those instructional voices as reminders of the sequence?*

AS : *Yes, ma'am, that's very helpful for me. If I hear the sequence, I don't need to look at the process again. Just use the numbers, ma'am.*

Students use previous results (area and number of sheets) in a new context (cost). The auditory learning style supports them in following step-by-step verbal instructions, for example, after knowing the number of sheets, they multiply it by the price. AS treats the results as final objects that can be used directly. AS remembers the structure of the question narratively, for example, in the question it is stated that after the cost of the grass, the shipping cost is added, so they do not need to re-analyze the previous process. Finally, AS adds up the results obtained, as shown in Figure 11.



Jumlah : 264.000 + 46.960
: 310.960

Translation:
Total = 264,000 + 46,960
= 310,960

Figure 11. Results of AS' confirmation

Researcher : *How do you know if your total result is correct?*

AS : *I repeat all the steps in my mind. I say them one by one: 'The area of the large circle minus the area of the small circle equals the area of the mini elephant grass. The area divided by the unit equals the number of grass sheets. The number of grass sheets multiplied by the price. The area multiplied by the shipping cost. Add them up.' If everything is in order and I haven't missed anything, then the answer is correct, ma'am.*

Researcher : *Don't you need to review the written steps?*

AS : *Sometimes not, ma'am. I believe more if I can repeat everything in my mind with my own voice, ma'am. That means I understand.*

AS calculates the total cost as a final step and shows that he is confident with the result. In the auditory learning style, students can confirm the correctness of their answers by repeating them silently in their minds or rereading the process they have done previously, such as listening to the explanation again. Overall, AS's problem-solving process based on the APOS theory can be seen in Figure 12.

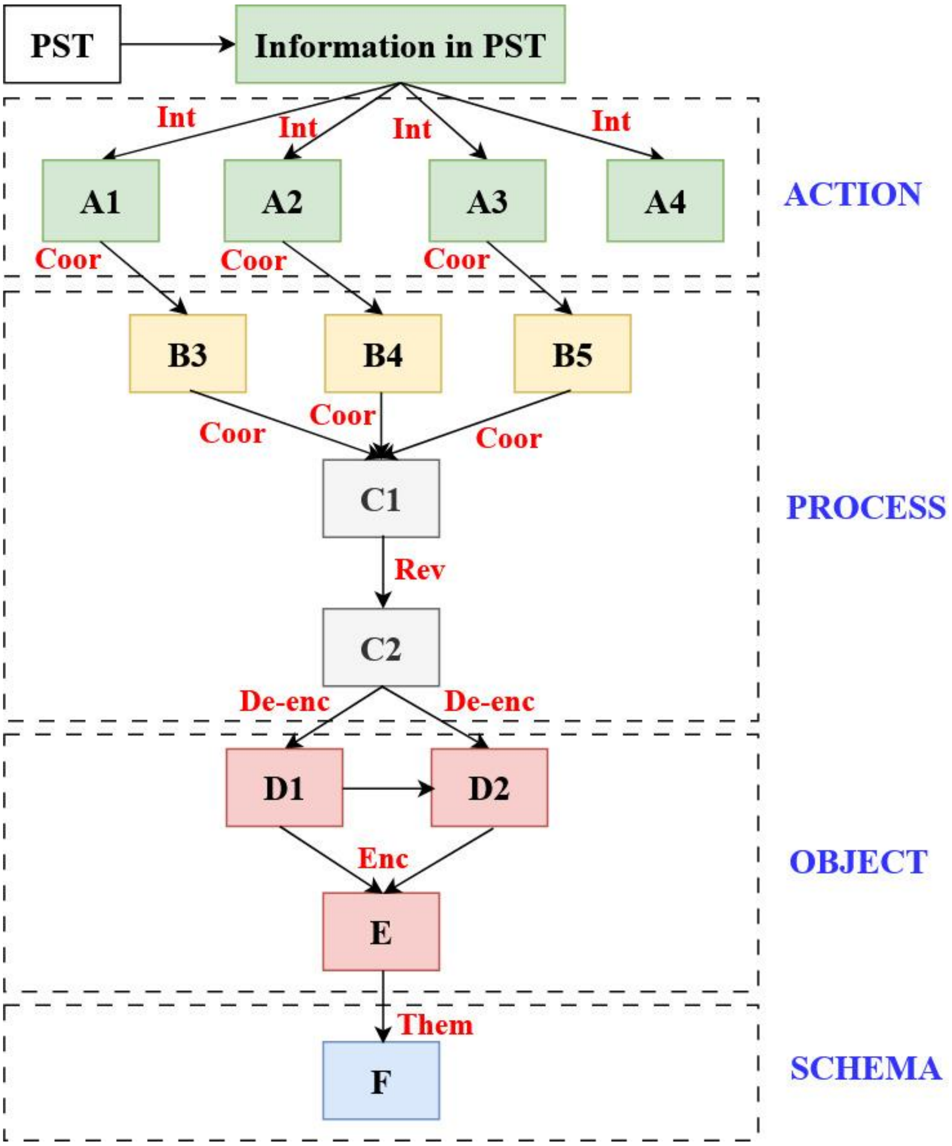


Figure 12. Analysis of AS' problem solving processes

The code description of Figure 12 about the Analysis of AS's problem-solving processes is presented in Table 5.

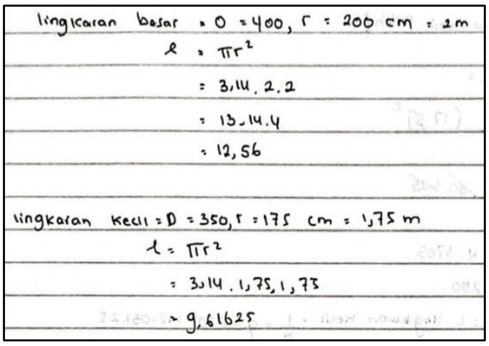
Table 5. Description of codes in Figure 12

Code	Description	Code	Description
PST	Problem Solving Test.	F	Designing a complete sequence of steps from the shape of the garden to the cost.
A1	Identifying the size of broad-leaved carpetgrass.	Int	Interiorization.
A2	Identifying the price per piece of grass.	Coor	Coordination.
A3	Identifying shipping costs per m^2.	Rev	Reversal.

Code	Description	Code	Description
A4	Identifying the objective: the lowest cost for purchasing broad-leaved carpetgrass.	De-enc	De-encapsulation.
B3	Calculating the area of large and small circles.	Enc	Encapsulation.
B4	Calculating the difference in area between two circles.	Them	Thematization.
B5	Converting the unit of area of a circle from cm^2 to m^2.	🟩	Reading and understanding the problem.
C1	Determining the area of one piece of broad-leaved carpetgrass.	🟧	Representing the problem.
C2	Calculating the amount of grass clippings needed.	⬜	Constructing problem-solving strategies.
D1	Multiplying the number of grass cuttings by the price per cut.	🟪	Solving problem.
D2	Multiplying the area by the shipping cost per m^2.	🟦	Confirming the answer.
E	Calculating the total cost of purchasing broad-leaved carpetgrass.		

Kinesthetic Student (KS)

After reading the question, KS identified what was known and what was being asked. KS converted the size of the broad-leaved carpetgrass to metres and then calculated the areas of the large and small circles, as shown in Figure 13.



lingkaran basar = D = 400, r = 200 cm = 2m
L = πr²
= 3,14 . 2 . 2
= 13.14.4
= 12,56

lingkaran kecil = D = 350, r = 175 cm = 1,75 m
L = πr²
= 3,14 . 1,75 , 1,73
= 9,61625

Translation:
Large circle: D = 400, r = 200 cm = 2 m
$L = \pi r^2$
= 3.14 x 2 x 2
= 3.14 x 4
= 12.56
Small circle: D = 350, r = 175 cm = 1.75 m
$L = \pi r^2$
= 3.14 x 1.75 x 1.75
= 9.61625

Figure 13. Results of KS' interiorization

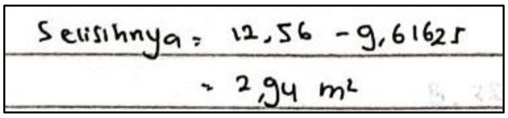
Researcher : *How do you start solving this problem, for example when calculating the area of two circles?*

KS : *First, I wrote down the data on paper. Then I imagined two circles that I drew in the air with my hands. I made a circular motion to imagine the circles. Then I used the formula πr^2 and calculated them one by one while writing.*

Researcher : *So you need to write while imagining the shape?*

KS : *Yes, that's right, ma'am. If I just read it, I forget quickly. But if I move my hands and write it down, I understand it better.*

KS calculates the area of two circles using the formula πr^2. Kinesthetic students usually understand when they write down the calculations physically or while imagining the shape of the circle concretely. They learn through the movements of calculating and writing, not just reading the formula. Then KS calculates the difference between the two circle areas as the area that will be planted with broad-leaved carpetgrass, as shown in Figure 14.



Selisihnya = 12,56 − 9,61625

= 2,94 m²

Translation:
The difference = 12.56 – 9.61625
= 2.94 m^2

Figure 14. Results of KS' coordination

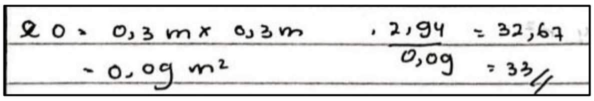
Researcher : *After obtaining the areas of the large and small circles, you subtract them. How do you know to do that?*

KS : *I imagined a large circle like a field, with a small circle like a pond in the middle. So the area that could be planted was the remaining outer part. I pointed to that part on the paper while reducing its value.*

Researcher : *Are you drawing it or just imagining it?*

KS : *Usually, I just draw small pictures on paper. But sometimes I also use my fingers to point out which parts to count, like painting shadows.*

KS coordinates the results of two circle areas to obtain the planting area. In a kinesthetic approach, students can imagine two circles as stacks of concrete objects and then imagine 'cutting' or 'taking' the middle part. The process of subtracting two circle areas is understood as a mental action or hand movement when writing. Figure 15 illustrates the process by which students determine the number of grass cuttings required.



L O = 0,3 m x 0,3 m

= 0,09 m²

$= \frac{2,94}{0,09} = 32,67$

= 33 //

Figure 15. Results of KS' reversal

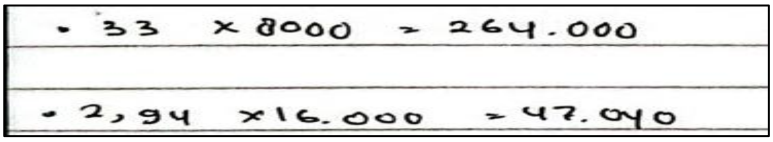
Researcher : *When you divide the total area by the area of one blade of grass, what do you imagine?*

KS : *I imagined the grass as a floor that needed to be tiled. Then I used my imagination to cut it into small squares. So it was like I was filling the field with grass tiles one by one.*

Researcher : *So you are imagining the physical process of filling the land?*

KS : *Yes, ma'am, I like to imagine real work like that. It makes it easier to think about, ma'am.*

KS reverses the process from total area to number of grass sheets. For kinesthetic students, this process can be associated with the physical activity of dividing or measuring an area into square sheets. KS understands that dividing the area by a small unit is like cutting or arranging a physical area into grass squares. Furthermore, KS calculates the cost of purchasing grass along with shipping costs, as shown in Figure 16.



• 33 × 8000 = 264.000

• 2,94 × 16.000 = 47.040

Figure 16. Results of KS' de-encapsulation and encapsulation

Researcher : *Once you know the number of sheets and the area, you can calculate the cost. What did you do at that time?*

KS : *I immediately write it down on paper, as if I were calculating my shopping expenses. I consider the number of sheets as the items I am holding, then I calculate the total price. Similarly, for the shipping cost, I write it down on paper and calculate it as if I were at the cashier.*

Researcher : *Do you feel the need to write down all the steps?*

KS : *Yes, ma'am. Writing is part of how I think. If I don't write it down, I find it difficult to focus, ma'am.*

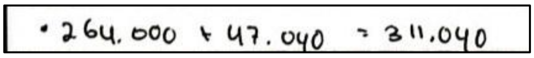
Researcher : *Yes, ma'am. Writing is part of how I think. If I don't write it down, I find it difficult to focus, ma'am.*

KS : *No, ma'am. I already wrote that clearly earlier. I just use it like taking numbers from my notes. It's like a price tag on goods, ma'am.*

Researcher : *So, by writing it down, you feel safe?*

KS : *Yes, ma'am. Once I have written it neatly and calculated it manually, I consider it final, ma'am.*

KS uses the results of the area calculation as a variable in the shipping cost calculation. It shows that students have 'opened' the previous object for a new process. Kinesthetic students usually write down all the steps as physical actions and rely on repeating the steps in reality, rather than just keeping them in their minds. Students treat the two results of the previous process as final units of information that can be directly added together. KS feels confident when the results are neatly written down and visualized on paper, so they treat them as fixed entities or objects. Finally, KS calculates the total purchase of mini elephant grass as shown in Figure 17.



• 264.000 + 47.040 = 311.040

Figure 17. Results of KS' confirmation

Researcher : *How do you know that the final result is correct?*

KS : *I recalculate by hand or using a calculator, ma'am. Sometimes I point out each step on the paper. If everything is in the order I made and the results are the same, then I am sure, ma'am.*

Researcher : *Do you prefer to check by movement or by writing again?*

KS : *Yes, ma'am, I will rewrite it or show you the process. That makes me feel confident and sure of my answer, ma'am.*

KS performs final verification by writing down the total sum. KS checks the final result actively, for example by physically recalculating, underlining, or mentioning it while rewriting it. The confirmation process is not only mental, but also performed through active repetition and writing sequences. For clarity, the results of the analysis of the KS problem-solving process based on APOS theory can be seen in Figure 18.

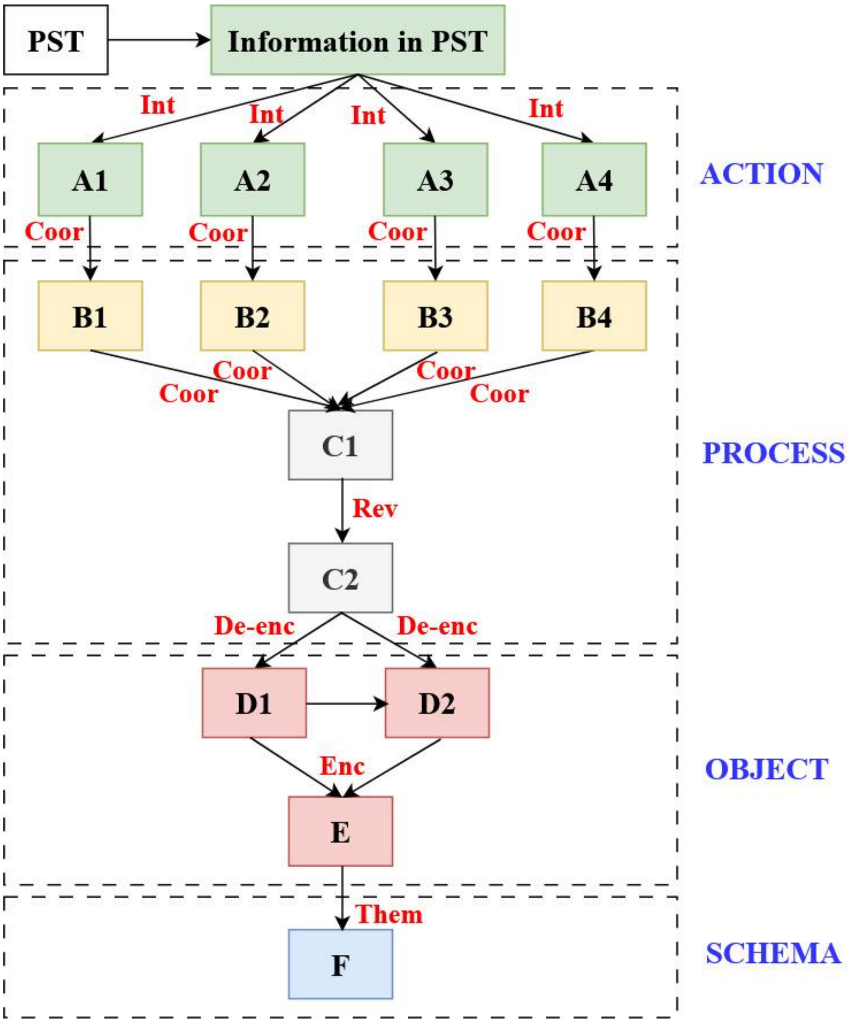


Figure 18. Analysis of KS' problem solving processes

The code description of Figure 18 about the Analysis of KS's problem-solving processes is presented in Table 6.

Table 6. Description of codes in Figure 18

Code	Description	Code	Description
PST	Problem Solving Test.	E	Calculating the total cost of purchasing broad-leaved carpetgrass.
A1	Identifying the size of broad-leaved carpetgrass.	F	Designing a complete sequence of steps from the shape of the garden to the cost.
A2	Identify the price per piece of grass.	Int	Interiorization.
A3	Identify shipping costs per m^2.	Coor	Coordination.

Code	Description	Code	Description
A4	Identify the objective: the lowest cost for purchasing broad-leaved carpetgrass.	Rev	Reversal.
B1	Determining the radii of the large and small circles.	De-enc	De-encapsulation.
B2	Changing the unit of the circle's radius from cm to m.	Enc	Encapsulation.
B3	Calculating the area of large and small circles.	Them	Thematization.
B4	Calculating the difference in area between two circles.	🟩	Reading and understanding the problem.
C1	Determining the area of one piece of broad-leaved carpetgrass.	🟧	Representing the problem.
C2	Calculating the amount of grass clippings required.	⬜	Constructing problem-solving strategies.
D1	Multiplying the number of grass cuttings by the price per cutting.	🟪	Solving problem.
D2	Multiplying the area by the shipping cost per m^2.	🟦	Confirming the answer.

3.2. Discussion

Mathematical problem-solving involves complex cognitive activity that integrates interpretation, representation, strategy development, and evaluation within contextual situations (Harisman et al., 2021; Riyadi et al., 2021; Susanti et al., 2023). Rather than restating the results, the present findings can be understood as illustrating how students' problem-solving processes emerge through the interaction between cognitive development (as conceptualized in APOS theory) and observable difficulties (as identified through NEA). This supports prior work suggesting that cognitive frameworks and diagnostic error analyses are not separate approaches but can be productively integrated to provide a more comprehensive account of students' mathematical thinking (Mubarokah & Amir, 2024; Yarman et al., 2024; Yerizon et al., 2025).

From a theoretical perspective, the findings extend existing literature by showing that learning styles may function as mediating tendencies in how students progress across APOS stages, rather than as fixed determinants of performance. While previous studies have highlighted the role of visual, auditory, and kinesthetic preferences in shaping engagement (Bosman & Schulze, 2018; Chetty et al., 2019; Purnomo et al., 2024), the present study suggests that these preferences intersect with specific cognitive demands at different stages. For instance, visual supports may facilitate representation, but do not necessarily prevent comprehension difficulties (Newman, 1977). This highlights a theoretical tension: learning styles can support access to information, yet they do not automatically ensure deeper conceptual understanding. Thus, the relationship between learning styles and problem-solving success should be interpreted as conditional and context-dependent rather than deterministic.

Furthermore, the distribution of errors across APOS stages suggests that difficulties in transformation and process skills are closely related to students' transitions from action to process and from process to object (Yarman et al., 2024; Yerizon et al., 2024). This finding aligns with Yerizon et al. (2025) notion that mathematical understanding develops through the encapsulation of processes into conceptual objects. However, the presence of TE even at higher stages indicates that progression through APOS is not strictly linear. Instead, students may demonstrate partial or uneven development, where advanced procedural coordination coexists with gaps in representation. This nuance contributes to the literature by challenging simplified interpretations of APOS as a strictly hierarchical progression.

Another important insight concerns the role of reflection in the final stages of problem solving. While some studies emphasize that errors in the verification stage are primarily due to carelessness (Baybayon & Lapinid, 2024; Siregar & Solfitri, 2019; Yerizon et al., 2024), the present findings suggest that such errors may also reflect incomplete integration at the schema stage. In this sense, EE should not be interpreted merely as indicators of accuracy, but as signs of how well students consolidate and communicate their understanding. This perspective reinforces the view that errors are not isolated mistakes but part of an ongoing cognitive construction process (Valdez & Taganap, 2024; Yarman et al., 2024; Yerizon et al., 2025).

In terms of pedagogical implications, the findings suggest that differentiated instruction should move beyond aligning teaching methods with students' learning preferences (Azizah et al., 2022; Harisman et al., 2019; Novrianti et al., 2025). Instead, instructional design should focus on supporting transitions between APOS stages while simultaneously addressing potential error patterns. Approaches such as guided discovery, visual representations, and the use of manipulatives can scaffold students' movement from action to schema (Arnon et al., 2014; Nga et al., 2023; Zagoto et al., 2025). At the same time, incorporating NEA as a formative assessment tool allows teachers to identify specific points of difficulty and provide targeted support (Köğce, 2022; Kurniati et al., 2021; Wardhani & Argaswari, 2022). This integrated approach aligns with the principles of student-centered learning promoted in the Merdeka Curriculum (Malacapay, 2019; Rijal et al., 2025).

Importantly, these findings also highlight a broader implication for mathematics education: addressing students' difficulties requires a shift from viewing errors as outcomes to understanding them as indicators of cognitive processes. By linking APOS theory with NEA, this study provides a structured way to interpret how students think, where breakdowns occur, and how instruction can respond to these challenges. This perspective is consistent with research emphasizing the importance of responsive and adaptive teaching in fostering higher-order thinking skills (Novrianti et al., 2025; Özdemir Baki et al., 2022; Pinzón et al., 2022).

In summary, this study contributes to the literature by offering an integrated framework that connects cognitive development, learning preferences, and error analysis in mathematical problem-solving. Rather than treating these dimensions separately, the study demonstrates how they intersect in shaping students' learning trajectories. This contribution is both theoretical by refining the application of APOS in relation to learning styles and error patterns and practical by informing the design of diagnostic and differentiated instructional strategies that support students' progression toward more advanced levels of mathematical understanding.

4. CONCLUSION

This study examined students' mathematical problem-solving processes by integrating APOS theory, learning styles, and NEA within a qualitative framework. The findings indicate that students demonstrated varied pathways in progressing through APOS stages, with most students reaching the object stage and a smaller number achieving the schema stage. Importantly, the in-depth analysis showed that all focal students were able to develop toward the schema stage through different modality-related pathways, suggesting that learning preferences do not hinder cognitive progression but may shape how students navigate problem-solving processes.

The analysis also identified patterns in students' difficulties across APOS stages. Reading and comprehension challenges were observed at earlier stages, while TE and PE appeared during the transition toward more advanced stages. No EE was identified in this dataset. These patterns should be interpreted as indicative tendencies rather than deterministic relationships, highlighting that learning styles may intersect with cognitive development in shaping students' problem-solving experiences.

This study is limited by its relatively small sample size and its focus on students from a single school, which may affect the generalizability of the findings. In addition, the use of a single contextual problem restricts the scope of observed problem-solving behaviors across different mathematical domains.

Future research is recommended to: (1) Design and empirically test instructional interventions that integrate APOS-based progression with modality-responsive learning activities; (2) Employ more diverse methodological approaches, such as mixed-methods designs and inter-rater reliability procedures to strengthen analytical robustness; and (3) Extend the application of this integrated framework to different mathematical domains, such as algebra, probability, and mathematical modeling, to examine its broader applicability.

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Declarations

Author Contribution	: KAH: Formal analysis, Investigation, and Writing - review & editing; Y: Conceptualization, Visualization, and Writing - original draft; Y: Formal analysis, Methodology, Supervision, and Validation; A: Methodology, Supervision, and Validation.
Funding Statement	: This research was funded by the Universitas Negeri Padang.
Conflict of Interest	: The authors declare no conflict of interest.
Additional Information	: Additional information is available for this paper.

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