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Mapping Students' Mental Models on the Material of Uniform Motion through Graphical Representation: A Cross Sectional Study

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ABSTRACT

Understanding uniform motion is fundamental in physics education as it serves as a basis for comprehending more advanced physical phenomena. Despite its importance, students often struggle with interpreting graphical representations of relationships between position, velocity, acceleration, and time, leading to misconceptions. This study aims to map students' mental models of uniform motion through graphical representations to identify their conceptual understanding and common misconceptions. A cross-sectional study design was used, involving 198 senior high school students aged 16–17 from a private school in Tangerang, Indonesia. Students completed five essay-based tasks requiring them to construct and interpret graphs related to uniform motion. Responses were analyzed using a rubric categorizing mental models into scientific, synthetic, or initial levels based on accuracy and depth of understanding. Results revealed diverse mental model categories, with most students displaying a partial knowledge of alternative conceptions or scientifically inaccurate interpretations. Findings emphasize the significance of visual representations in facilitating conceptual change and addressing misconceptions. The study concludes by offering insights into instructional strategies that enhance students' understanding of uniform motion, mainly through improved graphical representations. This research contributes to physics education by emphasizing the integrating mental models and visualizations to strengthen conceptual learning.

1. Introduction

Understanding the concept of regular straight motion is very important in science education, especially in physics because it is the basis for understanding more complex physical phenomena [1, 2]. Regular straight motion (RSM) characterized by constant speed and a fixed direction of motion helps students understand basic concepts such as speed, distance and time [3,4]. Through this understanding, students can develop the ability to analyze the movement of objects in everyday life, such as a vehicle moving at a fixed speed on a highway. In addition, the concept of regular straight

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motion provides an important foundation for understanding advanced physics concepts, such as acceleration, force, and Newton's laws, which will be easier to understand if students have mastered the basic principles of straight motion [5,6]. Mastery of the concept of regular straight motion also provides opportunities for students to develop abstract thinking skills. By understanding that the concept of constant velocity can be represented in graphs and equations, students can imagine how an object moves without needing to see it directly. This is an important skill in physics, where many concepts cannot be observed directly but understood through models and symbolization. Thus, an understanding of regular straight motion not only prepares students for more advanced physics lessons but also builds cognitive abilities that are essential in scientific analysis. One of the parameters that can be used to measure learners' cognitive abilities is mental models.

Mental models are an important parameter in measuring learners' cognitive abilities because they reflect the extent of their understanding of the concepts or phenomena being studied [7-9]. Mental models allow learners to form internal representations of scientific concepts, helping them to connect theory with reality [10-12]. When learners have mental models that are accurate and in line with scientific concepts, they are able to describe, predict, and explain various physical phenomena logically and deeply. The role of mental models in supporting the understanding of the concept of regular straight motion is crucial. Mental models are internal representations that a person has to describe or understand certain concepts more easily [11,13]. In the context of regular straight motion, a mental model can be a mental image of how an object moves at a fixed speed or a visual representation such as a distance-time graph. With a good mental model, students can connect abstract concepts in physics with real situations, thus facilitating the process of internalizing the concept. These mental models help students identify and correct misconceptions they may have, such as the assumption that when the velocity of an object is zero, the acceleration is also zero.

The identification of gaps in students' understanding of the concept of regular straight motion which is a basic concept in physics indicates an urgent need to map their mental models. Many students have difficulty in understanding the concept of regular straight motion due to various factors, such as the presence of misconceptions or limitations in connecting the theory with real situations. Misconception is a wrong or incorrect understanding or idea about a concept [14-16]. In the context of education, misconceptions often arise when students have an erroneous understanding of scientific concepts that are taught not in accordance with the severe conceptions of experts. Misconceptions can hinder students' learning process because they tend to maintain their wrong views even when given the correct explanation [17,18]. Learners have difficulty in distinguishing the quantities of position, velocity and acceleration [19-21], difficulty in interpreting graphs of the relationship between position, speed, acceleration, and time in straight motion [21–[25], and distinguishing between acceleration and gravitational acceleration in free fall motion and the effect of object mass on the speed of falling objects [26,27]. Some other misconceptions found in regular straight motion are (i) if the speed of an object in constant motion is large, then the acceleration of the object is also large; (ii) negative value velocity does not exist, or shows that the object is at rest; and (iii) All objects whose acceleration is zero are only at rest [28].

The misconceptions presented in previous studies only present a description and grouping of misconceptions [29,30]. However, no one has discussed in detail related to how internal representations, especially in visualizing graphs of the relationship between position, speed, acceleration, and time in straight motion. Misconceptions and conceptual chance certainly have an influence on students' mental models. This is because mental models are assumptions, strategies, perspectives, and rationale used and have deep roots in various actions [8,31,32]. According to Johnson-Laird [8]; Jones *et. al.,* [11]; Abdel-Raheem [33]; Hoemann *et. al.,* [34], mental models can be considered as cognitive frameworks or structures of understanding that include knowledge, beliefs, and mental representations of a concept. Based on the gap results, identifying and mapping students' mental models will provide a clearer picture of how they form an understanding of the concept, especially on straight motion material related to graphical depiction. By mapping mental models, educators can identify areas of understanding that are not in accordance with correct scientific concepts, so that they can design appropriate learning interventions. In addition, this mapping helps assess the extent to which students can interpret the relationship between position, velocity, acceleration and time in straight motion.

This research has important significance in understanding and improving students' understanding of the concept of regular straight motion, especially on the interpretation of graphs which is often misunderstood due to various misconceptions. By identifying common misconceptions related to how students' mental models interpret their knowledge in the form of graphs, it can be a new finding regarding to the mental model of students on straight motion material. This research offers new insights for educators in designing lessons that can construct students' concept understanding. Mapping and presenting the results of students' mental models allows educators to focus on areas of understanding that are not in accordance with correct scientific concepts, especially in the interpretation of graphs of the relationship between position, velocity, acceleration, and time. In addition, this research contributes to the development of targeted learning strategies, especially in visualization-based physics learning. By understanding students' mental models, educators can create learning approaches that not only correct misconceptions but also deepen students' conceptual understanding through more meaningful visual and graphic representations. This is expected to improve the quality of students' overall understanding and help students build a strong foundation in physics, which is important to support the learning of more complex physics concepts at the next level.

The purpose of this study is to conduct an in-depth analysis of students' mental models regarding the concept of regular straight motion. This analysis will help identify students' understanding of the core aspects of regular straight motion, especially on the relationship between the concepts of constant velocity, change in position, and the relationship between time and distance interpreted in the form of graphs. Graphical representation is expected to be able to visualize and describe students' mental models so that it can help students internalize the concept of regular straight motion better and facilitate the identification of correct understanding and conceptual errors that often occur. The research questions (RQ) answered in this study are as follows:

RQ1. How are students' mental models of regular straight motion mapped through graphic representations?

RQ2. How are the variations of students' mental models based on the results of graphic representations?

2. Methodology

2.1 Research Design

The research used a cross-sectional study in mapping students' mental models at a certain time. According to Wang and Cheng [35], cross-sectional study is an observational research conducted by collecting data at a certain time. This type of research is often used to look at a population or sample condition at a certain time. Research using cCross-sectional study aims to map students' mental models on regular straight motion material. In addition, the research design is in line with the concept of mental models that represent students' personal views of their cognition. Mental models are assumptions, strategies, perspectives, and rationale used and have deep roots in various actions [8, 36]. In this case, students will visualize the concept of straight motion in the form of a graph.

2.2 Participants

The participants in the study were 198 students from seven first-year Senior High School classes at a private school in Tangerang, Banten, Indonesia. Participants in the study were aged between 16-17 years old. Participants were selected based on criteria (e.g., having received uniform motion material and using Merdeka Curriculum). Merdeka Curriculum is a type of curriculum used by schools to guide the course of education in Indonesia. The personal identity of the students was safeguarded by guaranteeing their anonymity. Each participant was given 30 minutes to complete a test regarding mental models aimed at visualizing graphical representations of regular straight motion with teacher supervision during the test.

2.3 Data Collection Instruments

This data collection was designed to explore students' understanding of the concept of straight motion through their ability to create graphical representations. Using essay questions, students are expected to be able to describe the relationship between position, velocity, acceleration and time, so that it can be seen to what extent they understand the interrelationship of these variables in the context of straight motion. This approach makes it possible to evaluate students' mental models in depth, especially in terms of interpretation and construction of graphs that represent the relationship between the measured variables. A total of 5 questions were tested to see the representation of students' mental models. The distribution of the questions and an example of the form of the questions asked are presented in Table 1 and Figure 1. Figure 1 (a) depicts the questions in Indonesian and Figure 1 (b) depicts the questions in English.

Table 1
Distribution of graphical representation questions

No	Question
1	Draw a graph showing the relationship between distance and time in regular straight motion.
2	Draw a graph showing the relationship of position change to time in regular straight motion.
3	Draw a graph of velocity versus time in regular straight motion
4	Draw a graph of acceleration against time in regular straight motion
5	Draw a graph showing the relationship between displacement and time in regular straight motion.

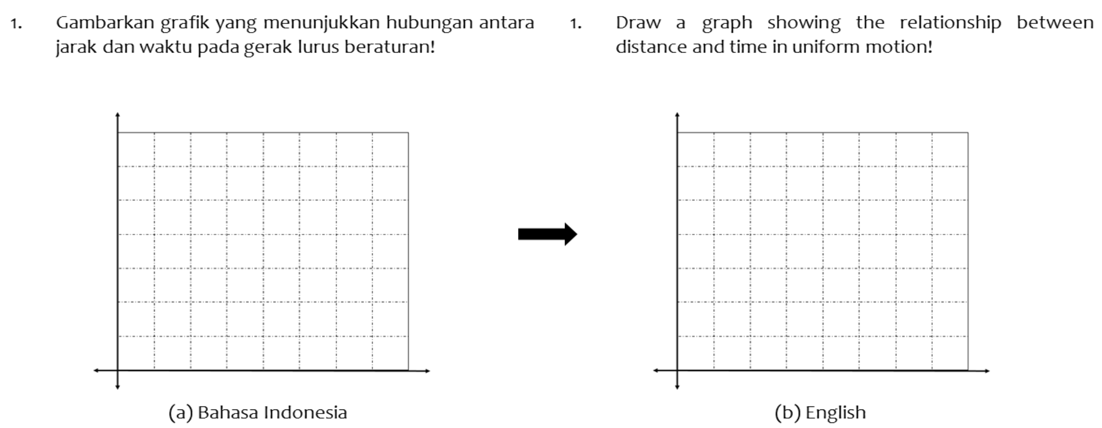

Fig. 1. An example for questions

2.4 Data Analysis

The data of this study were analyzed based on the category of students' level of understanding related to the interpretation of the graph. This study used a rubric referring to Kurnaz and Eksi [37] to reveal students' mental models. The summary of the rubric is presented in Table 2.

Table 2
Model mental evaluation rubric

Level of Understanding	Score	Criteria
"Sound understanding (SU)"	4	The answer contains all scientifically accepted components
"Partial understanding (PU)"	3	The answer contains some scientifically accepted components
"Partial understanding with alternative conception (PU-AC)"	2	The answer shows the concept can be understood but also contains other conceptions
"Alternative conception (AC)"	1	The answers that are scientifically incorrect and contain incorrect information
"No understanding (NU)"	0	Blank, irrelevant, and unclear answers

Understanding is indeed an important thing to pay attention to students who are not only verbally but also visually. This study focuses on students' understanding of graph visualization related to the relationship between variables. The results of students' answers are then categorized according to the categories contained in Table 2. Then proceed with the level of understanding category presented in Table 3.

Table 3
Category for model mental

Category	Criteria	Level of Understanding
"Scientific"	"Perceptions that coincide at level 4 (SU) or level 3 (PU)"	3 and 4
"Synthetic"	"Perceptions that partially coincide or do not correspond to knowledge coincide at level 2 (PU-AC)"	2
"Initial"	"Perceptions that do not match knowledge. Answers are at level 0 (NU) and level 1 (AC)"	0 and 1

3. Results
3.1 Grouping Students' Mental Models

The results in this section present the grouping of categories of students' mental models of regular straight motion through graphical representations. The first grouping will refer to the evaluation of level of understanding (Table 2) and continued to the mental model category (Table 3). The evaluation and categorization of mental models are presented as follows.

3.1.1 Evaluation of mental models

Figure 2 shows the students' level of understanding of the five questions (Q1 to Q5) based on the following categories: scientific understanding (SU), partial understanding (PU), partial understanding with alternative conception (PU-AC), alternative conception (AC), and no understanding (NU). Each category is represented with a different color, illustrating the distribution of students' level of understanding on each question. In Q1, most students were in the Partial Understanding with alternative conception (PU-AC) category (97 students), followed by Partial Understanding (PU) (63 students). In contrast, the scientific understanding (SU) category was barely visible, with only 1 student having scientific understanding. A similar trend was seen in Q2 and Q3, where the PU-AC category dominated with a high number of students (102 and 118 students, respectively). The alternative conception (AC) category did not appear at all in these two questions, indicating that students tended to have mixed but less scientific understanding.

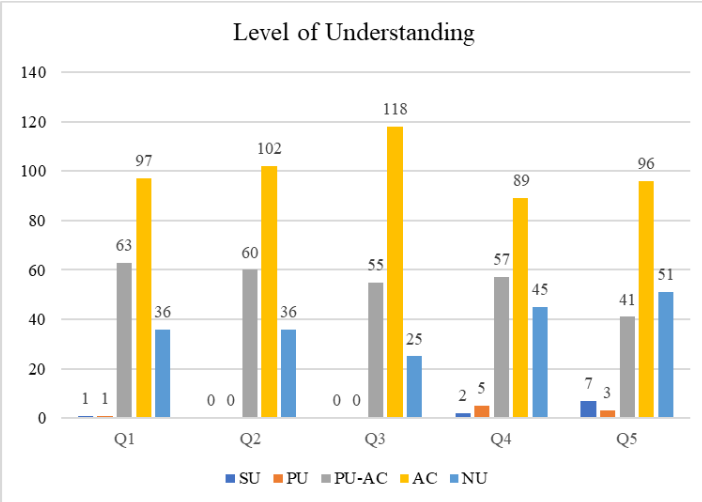

Fig. 2. Evaluation of mental models

Additionally, in Q4 and Q5, there was a more significant shift to the partial understanding (PU) category (57 and 51 students, respectively). However, PU-AC still dominated the number of students (89 and 96 students, respectively). Interestingly, the no understanding (NU) category started to appear more frequently in Q4 and Q5 compared to the previous questions, although the number remained small. Overall Figure 2 shows that the majority of students had partial understanding with some misconceptions, and only a small proportion achieved full scientific understanding. This indicates the need for more effective learning interventions to improve mental models and increase the level of scientific understanding in representing the concept of regular straight motion in graphical form.

3.1.2 Evaluation of mental models

Figure 3 shows the categories of students' mental models for the five questions (Q1 to Q5), classified into three categories: scientific, synthetic, and initial. These categories illustrate students' level of understanding from scientific understanding to incomplete initial understanding. In Q1, the majority of students were in the Initial category with a total of 133 students, indicating a very dominating initial understanding. A total of 63 students were in the Synthetic category, indicating a mix of correct and incorrect understanding. However, only 2 students reached the Scientific category, meaning only a small percentage of students understood the concept scientifically. A similar trend is seen in Q2 to Q5, where the Initial category continues to dominate (with 138, 143, 134, and 147 students, respectively), indicating that most students are at an early stage of understanding without fully mastering the correct concept.

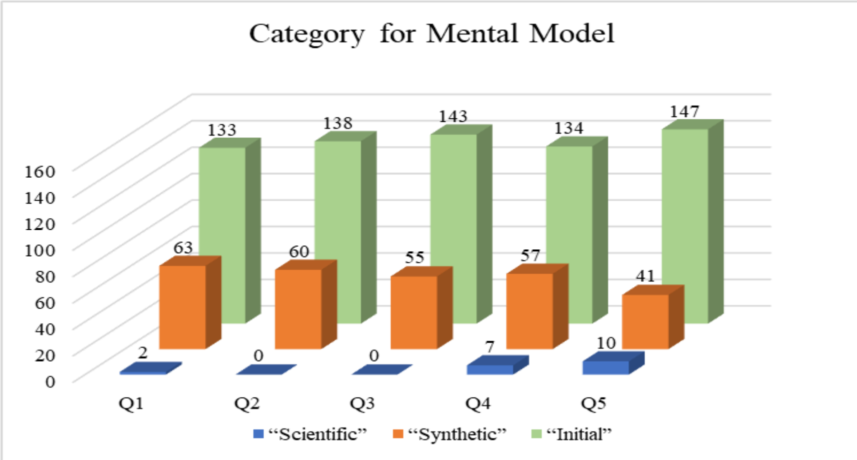

Fig. 3. Category of students' mental models

In the Scientific category, the number of students remained low throughout all questions, although there was a small increase in Q5 (10 students). On the other hand, the synthetic category showed fluctuations, with the highest number in Q1 (63 students) and a gradual decrease in Q5 (41 students). Overall, this graph shows that most students are still at the Initial stage of concept understanding and only a few have achieved full scientific understanding. This highlights the need for more structured and effective learning strategies to encourage students' transition from initial mental models to scientific mental models, especially in visualizing in the form of graphs.

3.2 Variation of Students' Mental Models based on Graphical Representation Results

The results in this section present the variation of students' mental models based on the results of the graphs they have worked on. The variation of mental models will be presented based on the answers in Q1 to Q5. The mental model variations are presented as follows.

3.2.1 The mental model of question 1

Question 1 asks students to describe how the graph of the relationship between distance and time in regular straight motion is characterized by a constant velocity. The graph of this relationship should be a straight line that rises linearly from the origin with a fixed slope. The slope of the line represents the velocity of the object, so if the velocity is fixed, the slope of the graph is also fixed. The graph should not curve, change, or return to the time axis because this contradicts the nature of RSM which always moves at a fixed speed. Some student answers are presented in Figure 4.

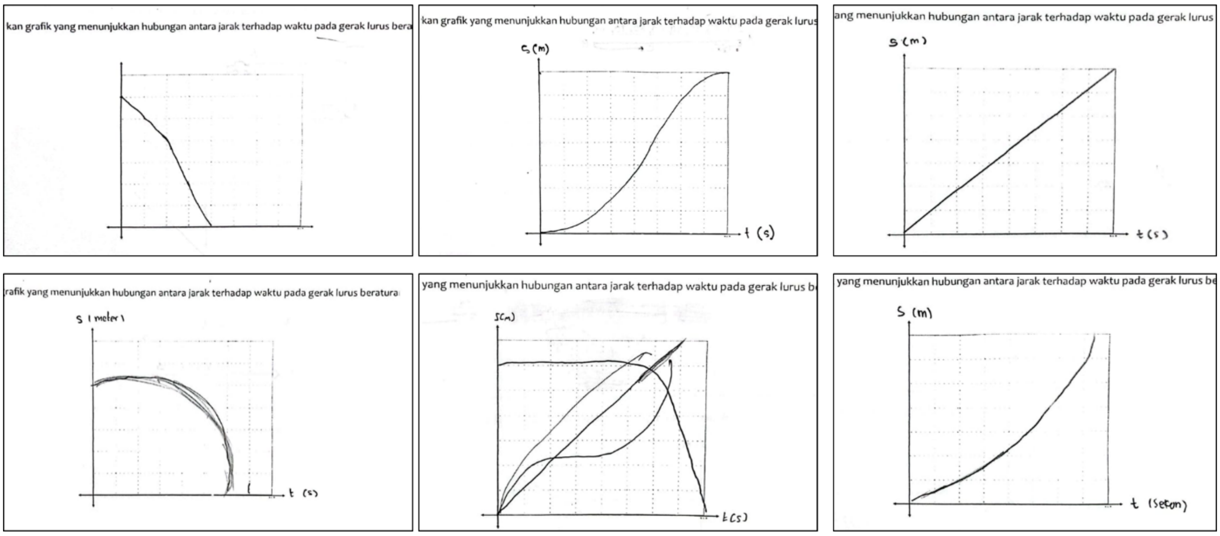

Fig. 4. Students' mental model on the relationship of distance to time

Based on the graphs drawn by students in Figure 4, there are many that are not in accordance with the concept of RSM. Some of the graphs show an upward or downward curved shape, which indicates acceleration or deceleration. There are also graphs with changing slopes, which reflect inconstant speed, and graphs that stop or even return to the time axis, which is a misinterpretation of distance. These errors indicate student misconceptions, both in understanding the meaning of graph slope as speed and in applying the concept of RSM.

3.2.2 The mental model of question 2

Question 2 asks students to draw a graph of the change in position versus time in regular straight motion. The graph of this relationship should be a straight line that rises linearly from the origin with a fixed slope. The slope of the line represents the velocity of the object, so if the velocity is fixed, the slope of the graph is also fixed. This is similar to the graphs of distance versus time and displacement versus time with constant velocity. These graphs should not be curved and have only one line. Some student answers are presented in Figure 5.

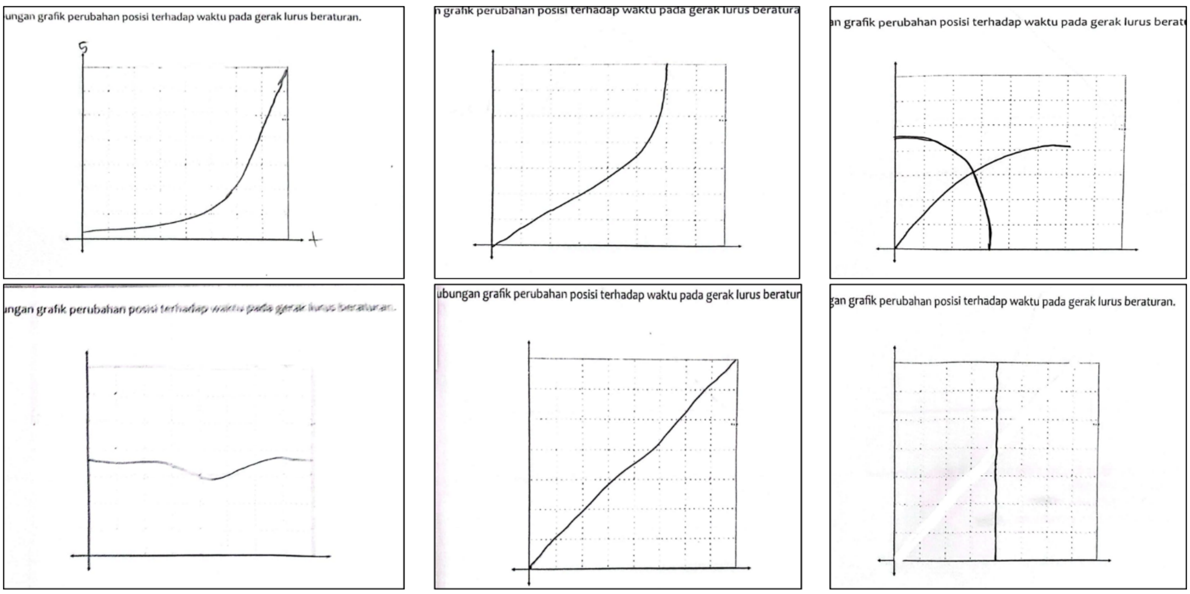

Fig. 5. Students' mental models on the relationship of the graph of position change to time

3.2.3 The mental model of question 3

Question 3 asks students to draw a graph of velocity against time in regular straight motion. The graph presented must be straight and in line with time without any slope. Therefore, the graph must be horizontal and in a non-zero position v (constant). Some students' answers are presented in Figure 6.

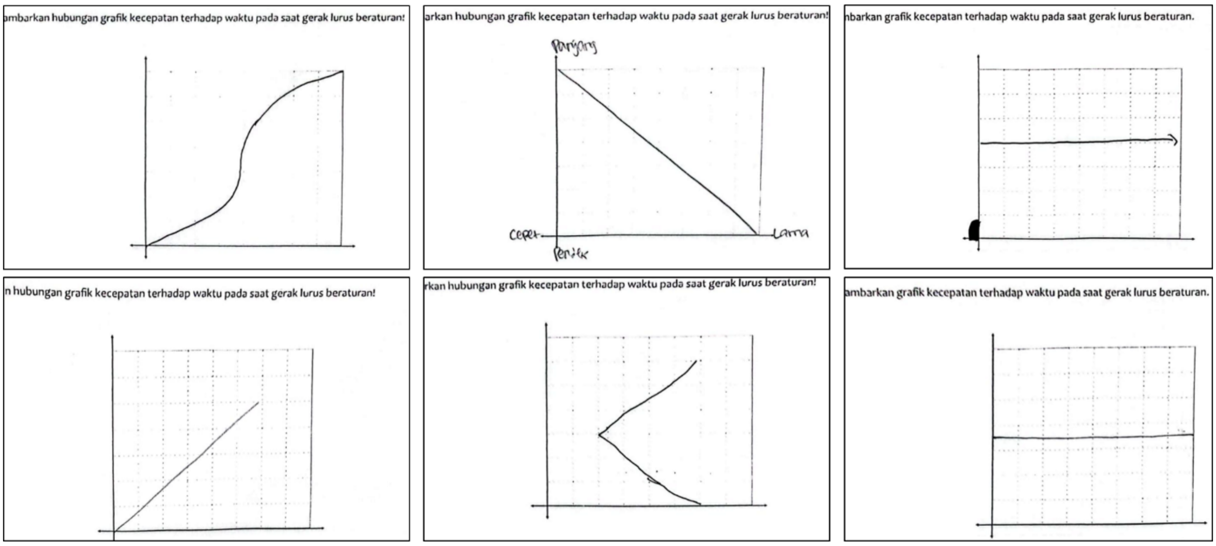

Fig. 6. Students' mental models on the relationship of velocity to time graphs

3.2.4 The mental model of question 4

Question 4 asks students to draw a graph of acceleration against time in regular straight motion. The graph presented must be straight and linear with time without any slope. Therefore, the graph must be horizontal and parallel to the timeline position. This is because, when the velocity (v) is constant, the acceleration is zero. Some student answers are presented in Figure 7.

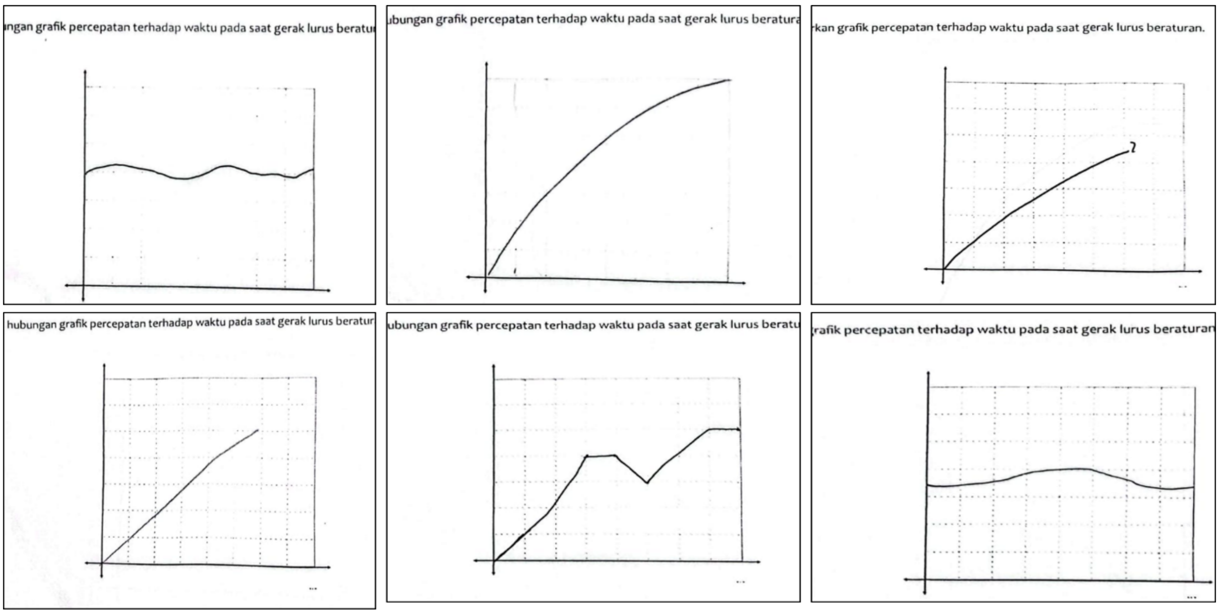

Fig. 7. Students' mental models on the relationship of acceleration to time graphs

3.2.5 The mental model of question 5

Question 5 asks students to graph the relationship of displacement to time in regular straight motion. The graph of this relationship should be a straight line that rises linearly from the origin with a fixed slope. The slope of the line should be the same as the graphs of distance with respect to time and change in position with respect to time at constant speed. The graph should not be curved and should have only one line. Some student answers are presented in Figure 8.

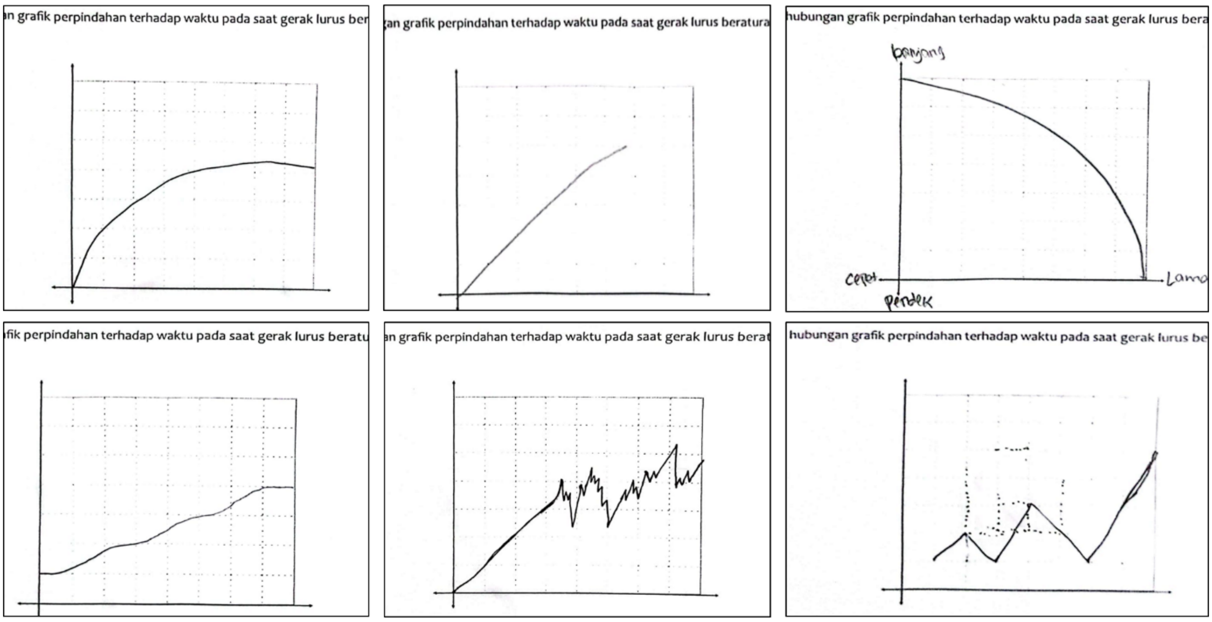

Fig. 8. Students' mental models on the relationship of displacement to time graphs in motion

4. Discussion

The results of grouping students' mental models based on understanding categories (scientific understanding, partial understanding, partial understanding with alternative conception, alternative conception, and no understanding) showed that the majority of students were at the level of partial understanding with misconceptions (PU-AC) and initial understanding (Initial). This was particularly striking in the first question (Q1), where only 1 student reached the scientific understanding (SU) category, while most students (97 students) were in the PU-AC category. A similar pattern was seen in other questions, especially Q2 and Q3, with the PU-AC category dominating. This finding indicates a significant gap between what is expected scientifically and what students understand in representing the concept of regular straight motion, especially visualization graphically. In fact, according to Beichner [38]; Kozhevnikov and Thornton [39]; Volkwyn *et. al.,* [40], graphic representations are effective in helping students understand the relationship between variables such as position, velocity, and time in straight motion.

When further examined, the Initial category dominates the results of the grouping of students' mental models (Figure 3). A total of 133 students fell into the Initial category in Q1, while only 2 students made it to the Scientific category. The dominance of the Initial category indicates that most students have not been able to integrate the basic concept of RSM into the correct graphical representation. Even in Q5, where there was a small increase in the Scientific category (10 students), the number of students in the Initial category remained high (147 students). This reflects that students' ability to achieve scientific understanding through graphic representations is still lacking. This is in line with the findings of Bollen *et. al.,* [41]; Meltzer [42]; Glazer [43], that graphical representations play an important role in helping students understand the relationships between physics variables, but are often less effectively used in learning due to students' limited analytical skills.

Graphical representations actually have great potential to clarify the concept of regular straight motion [44-46]. However, the findings show that graphs are instead a source of misconceptions for many students. For example, in Q1, the graphs that students drew were often curved or had an arbitrary slope, indicating students' lack of understanding of the relationship between constant velocity and the slope of the graph. Similar errors were seen in Q3, where the graph of velocity against time should have been horizontal but many students drew graphs with a certain slope or even down to zero, reflecting a reduced velocity. These failures indicate that the utilization of graphs in learning requires a more structured and explicit approach. Media such as Augmented Reality (AR) can be used to help students understand the dynamic representation of graphs, for example by showing how changes in time or distance variables affect the shape of the graph. In addition, discussion-based learning can help students identify errors in their graphs and compare them with correct scientific concepts.

This finding is in line with the research results of McDermott *et. al.,* [45]; Glazer [43], which showed that students often misunderstand graphs as physical representations of moving objects, not mathematical relationships between variables. Research by Beichner [38]; Ubuz [47] ; Ivanjek *et. al.,* [48], also highlights that students' misconceptions regarding graphs often stem from a lack of basic understanding of the meaning of slope and the shape of the graph. However, this study made an additional contribution by grouping students into mental model categories (initial, synthetic, and scientific) which showed that most students were still at the Initial stage of understanding. Interestingly, the Synthetic category, which reflects a mix of correct and incorrect understanding, did not show significant progress. In fact, the number of students in this category actually decreased from Q1 (63 students) to Q5 (41 students). This indicates that without effective learning interventions, students are less likely to transition from their initial mental models to a more scientific understanding, despite repeated exposure to the concepts.

This finding shows the importance of visual-based and interactive learning approaches to help students understand the relationship between variables in RSM. Graphical representations need to be explained with relevant contexts so that students not only see graphs as images, but also understand the mathematical meaning behind them. The use of technology-based simulations such as AR can be a solution to address recurring misconceptions, while collaborative discussions can provide opportunities for students to criticize their mistakes. This is in line with the results of research that discusses the contribution of AR in overcoming misconceptions [49-50]. In addition, teachers need to provide structured exercises that emphasize the relationship between graphs and physical concepts, such as how the slope of a graph indicates velocity or how a horizontal shape indicates zero acceleration. Thus, students can be encouraged to transition from the Initial to scientific category, while reducing the dominance of the PU-AC category which is still very high in almost all questions. This combination of learning strategies is expected to significantly improve students' understanding.

5. Conclusions

This study reveals that most students exhibit partial understanding with misconceptions (PU-AC) when interpreting graphical representations of uniform linear motion (RSM). Analysis of mental models categorizes students into three groups: Initial, Synthetic, and Scientific, with most students remaining in the Initial category, suggesting an incomplete or incorrect grasp of fundamental concepts like velocity, position, and acceleration. The evaluation of graphical representations highlights common student errors, such as misinterpreting the slope of position-time graphs or depicting velocity-time graphs with varying slopes, indicating that students need help to connect abstract mathematical relationships to physical phenomena. These findings emphasize the need for more structured, interactive, and visually-rich teaching strategies, such as integrating Augmented Reality (AR), to help bridge the gap between initial and scientific understanding.

One limitation of this study is its focus on a specific group of students within a particular context, which may not represent broader student populations across different educational settings or cultural contexts. Additionally, the study only addresses a narrow range of questions related to uniform linear motion, and students' conceptual understanding could vary significantly for other physics concepts or more complex motion models. The reliance on paper-based responses also limits the potential for real-time analysis of student thought processes, which could be better captured through interactive digital tools or more dynamic assessment methods.

Future research could explore using more advanced technological tools, such as interactive simulations and AR, to further investigate how dynamic visualizations can influence student understanding of motion. Additionally, longitudinal studies that track changes in students' mental models over time would provide valuable insights into how conceptual understanding evolves with continued exposure to more sophisticated learning tools. Further studies could also expand the scope to include a wider variety of topics in physics, evaluate how different types of graphical representations impact understanding across various domains of science, and should consider including a more diverse sample of students from different regions, backgrounds, and educational systems. Moreover, investigating the role of collaborative learning and peer discussions in improving graphical interpretation could yield fruitful insights into effective pedagogical strategies for overcoming misconceptions.

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