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Coordinating Multiple Representations in Mechanics: A Mixed-Methods Analysis of Prospective Physics Teachers

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Abstract: This exploratory case study investigates the multiple representational skills of prospective physics teachers in solving mechanics problems within a specific institutional context. The study employed a mixed-method approach to obtain both quantitative and qualitative insights into students' representational skills. The participants were 17 second-semester students enrolled in a Physics Education program at a public university in Langsa City, Indonesia, representing a bounded institutional case. Data were collected using a validated test comprising 11 mechanics problems across four types of representations (tabular, graphical, diagrammatic, and mathematical). Follow-up semi-structured interviews were conducted with three randomly selected participants to explore their reasoning processes and representational difficulties. Quantitative data were analyzed using descriptive statistics and the Friedman test to examine differences across representation types. Qualitative data from interviews were analyzed using thematic analysis to identify recurring patterns of challenges and reasoning strategies. The findings revealed statistically significant differences in students' performance across representation types ($\chi^2 = 8.77, p = .033$) Students demonstrated the highest skill in tabular representations, followed by mathematical and diagrammatic representations, while graphical representations emerged as the weakest area. Qualitative findings indicated that students relied heavily on formula-based problem-solving, experienced difficulty interpreting graphs and diagrams, and struggled to translate and coordinate across representations. The results suggest that prospective physics teachers possess uneven representational skills, characterized by procedural strength in symbolic manipulation but weaknesses in visual interpretation and representational coordination. These findings highlight the need for explicit training in multiple representations, collaborative learning, and scaffolded instruction in physics teacher education. However, the conclusions should be interpreted cautiously due to the small sample drawn from a single institution. Future research with larger and more diverse samples is recommended.

Keywords: multiple representation, prospective physics teacher, mechanics, mix-methods analysis.

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■ INTRODUCTION

Despite the central role of multiple representations in physics problem solving, empirical evidence indicates that students often struggle to use and coordinate different forms of representation effectively (Galili, 1996; Nieminen et al., 2017), particularly in mathematically intensive domains such as mechanics. Research has shown that learners frequently rely on a single, familiar representation while encountering persistent difficulties in interpreting graphs, constructing and relating diagrams, and translating physical situations into appropriate mathematical expressions (Kind et al., 2017; Kohl & Finkelstein, 2017). Such difficulties arise because effective learning in physics requires not only understanding individual representations, but also the ability to flexibly translate and integrate information across graphical, diagrammatic, and mathematical forms (Kuo et al., 2017). This imbalance in representational skill is particularly problematic in mechanics, where conceptual understanding depends heavily on coordinating multiple representations to reason about motion, forces, and relationships between variables. In teacher education contexts, these limitations may have long-term consequences, as prospective teachers with underdeveloped representational skills may struggle to design instruction that supports students' conceptual understanding and scientific reasoning. Despite extensive theoretical discussions on the importance of multiple representations, systematic empirical evidence describing the profile of multiple representational skills among prospective physics teachers remains limited, especially at the undergraduate level (Kohl & Finkelstein, 2017).

Physics, as a conceptual discipline, is primarily articulated using mathematical language, and physicists utilize mathematical models to anticipate the behavior of natural systems. Additionally, as a science based on physical phenomena, physics also requires visuals to observe and study phenomena as they occur. However, studying, predicting, and solving problems related to these phenomena need not be done through real objects or actual events. For considerations of efficiency and effectiveness, sometimes learning physics must be done through images or other non-real media. Problem-solving with representations can be displayed through images (visual), words (verbal), tables, graphs, or mathematical (Ertikanto et al., 2018). In this context, multiple representations become the means to achieve the intended goal (Kuo et al., 2017). Therefore, representation plays a vital role in explaining physical phenomena or real events (M.-A. Geyer & Kuske-Janßen, 2019; Yeo & Gilbert, 2017). Thus, there is a need for skills to represent real phenomena in other forms, known as multiple representational skills. In short, it is the skill of representing or explaining physics concepts in various forms/formats such as verbal descriptions, images, symbols, diagrams, graphs, and mathematical equations (Munfaridah et al., 2022; Opfermann et al., 2021).

Physics is perceived as a difficult subject because it requires students to tackle problems using multiple representations and manage the relationships between those representations (Guttersrud & Angell, 2010). This makes multiple representational skills important for students to master (Kind et al., 2017; Opfermann et al., 2017) especially for physics or physics education students. The skill to manipulate understanding of mathematical contexts, accompanied by illustrative images or data in the form of tables, enables students to better grasp the physics concepts themselves (Ainsworth, 2006, 2008). Physics will be easier to understand if it involves various models of representation, such as mathematical models, symbols, images, diagrams, tables, graphs, illustrations, and even simulations and animations involving computer technology (Nikat et al., 2021). There is much evidence showing that multiple representation plays a role in supporting physics learning (Ainsworth, 2006).

Prospective physics teachers must be able to master multiple representational skills (Koswojo et al., 2024; Kurnaz, 2013; Subali et al., 2015). A learning environment that offers diverse forms of representation strengthens students' problem-solving skills (Koswojo et al., 2024). Despite the well-documented advantages of multiple representations (MR), empirical research indicates that prospective science teachers, including those holding undergraduate degrees in science, often struggle to employ them effectively in science instruction (Conceição et al., 2021; Lunsford et al., 2007; Roth et al., 1998). For physics teachers, strong multiple-representational skills are essential, as they enable them to communicate physics concepts through various complementary forms. Since different students may benefit from different representational modes, the coordinated use of tables, graphs, verbal explanations, and mathematical expressions can enhance conceptual understanding by offering multiple access points to the same idea (Ainsworth, 2018). Our previous research on high school students (in a certain school) found that table, verbal, and graph representations are still relatively low (Yakob et al., 2023). We suspect that one of the contributing factors is the teacher's skill in mastering multiple representations. Therefore, this study was designed as an exploratory case study to examine prospective physics teachers' multiple representational skills within a specific institutional context. Rather than aiming to produce a generalizable profile, this study seeks to provide an in-depth understanding of representational strengths, weaknesses, and challenges in a bounded educational setting. The findings are intended to generate preliminary insights and inform future large-scale investigations in physics teacher education.

The most difficult representations for students are pictorial (images/diagrams) and graphs. Students' understanding related to graphs is closely related to their mathematical understanding. Likewise, mathematical understanding becomes crucial because it is closely related to understanding graphs through functions and algebra (Sezen et al., 2012). Students are still having difficulty formulating mathematical equations from the graphs they create, resulting in less sharp interpretations; they only read the trend lines on kinematic graphs without associating them with their physical meanings (Subali et al., 2015). Students' low pictorial and graphical representation skills stem from their more frequent use of mathematical formats to solve physics problems, accompanied by verbal explanations. Students have difficulty depicting relationships between variables in the form of graphs (Marpaung & Setiawan, 2016).

One example of physics material that requires graphical explanations is mechanics. In planar kinematics, students are expected to understand vectors and the Cartesian plane. The Cartesian plane serves as a medium for understanding vectors because we can see a vector's direction and observe the difference in magnitude between two vectors from the displayed graph. Two different vectors, when added, will produce a vector different from the previous vectors, and this can only be seen at least on the Cartesian plane (Sommerfeld, 1952).

Difficulties in coordinating and translating between multiple representations in mechanics have been widely reported in the literature. Studies have shown that university students, including engineering majors, tend to rely predominantly on mathematical representations while struggling with graphical, diagrammatic, and conceptual forms (Nguyen & Rebello, 2011; Niyomufasha et al., 2024). Common challenges include difficulties in interpreting graphs, constructing free-body diagrams, and linking mathematical procedures to physical meaning (Nguyen & Rebello, 2011). Although multiple representations are recognized as essential for developing deeper conceptual understanding in mechanics (Wong et al., 2011), students frequently experience obstacles when shifting across representational forms. Within this broader context, similar patterns have been observed in our institutional setting, where learning outcomes in the Mechanics course have remained consistently unsatisfactory, particularly in topics involving mathematical modeling and vector analysis. Given that mechanics relies heavily on the coordinated use of mathematical, graphical, and diagrammatic representations, limited representational skill may constrain students' conceptual understanding and problem-solving performance, as students often experience difficulties in integrating and translating between representations (Munfaridah et al., 2021; Savinainen et al., 2013). The research questions that become the focus in this study are: 1. What is the level of skill of prospective physics teachers in tabular, graphical, diagrammatic, and mathematical representations in solving mechanics problems?; 2. Are there statistically significant differences in performance across these representational forms?; 3. What challenges do students encounter in interpreting and coordinating these representations?.

■ METHOD

Participants

The population of this study consisted of all second-semester students enrolled in the Physics Education programs across universities in Langsa City, who are prospective physics teachers. The sample comprised 17 second-semester students in Physics Education from one public university in Langsa City. All participants had completed the Mechanics course during the study period. As a conceptual foundation, the participants had previously completed the Basic Physics 1 course, which serves as prerequisite knowledge for learning mechanics concepts. Given these characteristics, the participants were considered appropriate for this study, as they had already acquired foundational knowledge from Basic Physics 1 and were in the process of strengthening and developing their understanding through Mechanics instruction in the second semester.

Research Design and Procedures

This study employed a mixed-method with an exploratory case study design (Creswell & Creswell, 2023) to examine the representational skills of prospective physics teachers within a bounded institutional context. A validated 11-item instrument was administered to 17 students in second-semester physics education. Assessments were conducted sequentially over three weeks. In the first week, students were given the Linear Motion Kinematics material, culminating with the completion of four problems in set A. In the second week, students were given the advanced material, Particle Dynamics, and culminated with the completion of two problems in set B. Finally, in the third week, students were given reinforcement of the two previous materials, which culminated in the completion of five problems in set C. Student responses were evaluated using a predetermined scoring rubric to ensure consistency of measurement across different types of representations.

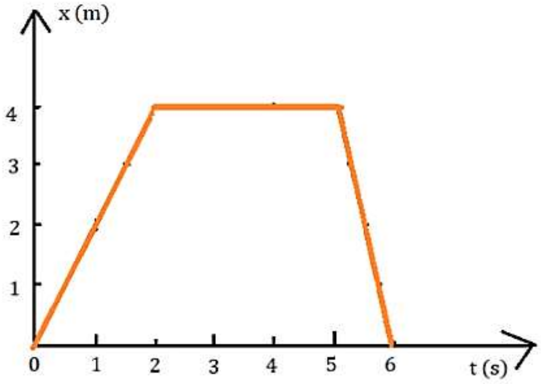
To complement the quantitative results, semi-structured interviews were conducted with three students selected randomly from the participant pool. The interviews aimed to explore students' reasoning processes, representational preferences, and difficulties encountered when interpreting and coordinating multiple representations. Each interview lasted approximately 20-30 minutes and was audio-recorded with participants' consent. This qualitative component was intended to provide deeper insight into the patterns observed in the statistical findings.

Instruments

A preliminary instrument was developed to assess students' multiple representational skills, comprising three groups of questions (A, B, and C). The initial draft comprised 25 items; however, after validation and refinement by two experts with more than 15 years of experience as physics education lecturers, the final instrument used in this study comprised 11 items. The first group (set A) included four multiple-choice items, each accompanied by a justification for the selected answer. These questions were related to the topic of linear motion kinematics. Set B consisted of 2 essay questions related to particle dynamics in one dimension. Set C consisted of 2 multiple-choice questions and 3 essay questions on the topics of linear motion, kinematics, and particle dynamics in one dimension. The instruments are depicted in Table 1. The reliability coefficients for each question package, in sequence, were 0.83, 0.76, and 0.73. One of the questions in each set is shown as follows.

To enrich this quantitative test, semi-structured interviews were also conducted and then examined to assess the degree of consistency, logical coherence, and causal linkages between participants' written and oral responses. The questions asked focused on experience in studying mechanics and the use and understanding of tabular, graphical, mathematical, and diagrammatic representations. Follow-up questions were also asked to deepen the understanding if necessary. Some examples of questions asked include: "Which representation do you feel most comfortable using? Why?"; "How do tables help you understand a mechanics problem?"; "What difficulties do you experience when interpreting graphs?"; etc.

Set A:



"The correct statement related to the graph is...

a. The distance traveled by the object during 6 seconds is 4 meters.

b. During $0 \leq t \leq 3$*the object is displaced by 4 meters.*

c. During$0 \leq t \leq 5$*ng the object travels 4 meters to the right.*

d. Throughout the motion, the object experiences no displacement.

e. From the 2nd to the 5th second, the object travels a distance of 12 meters.

The reason you chose that answer:

a. The area between the and 5th second is 12 units.

b. During the motion, the farthest path traveled by the object is 4 meters.

c. The difference in position between the and second is 4 meters.

d. At $t \leq 5$ *, the object moves along a path 4 meters to the right from its initial position.*

e. During the 6 seconds, the object returns to its initial position.

Set B: *"A particle with mass is initially at rest at time . A force along the -axis is applied to the particle. The magnitude of this force increases with time and is given by . Determine the distance traveled by the particle as a function of time!."*

Set C: *"The motion of a particle is described by the following equations. Find the velocity and acceleration, giving a geometrical interpretation, if any, in each case.*

a) $\boldsymbol{r} = at\hat{\boldsymbol{\imath}} + bt^2\hat{\boldsymbol{\jmath}}$

b) $\boldsymbol{r} = at\hat{\boldsymbol{\imath}} + \boldsymbol{A}\ \cos\omega t\,\hat{\boldsymbol{\jmath}}$

c) $\boldsymbol{r} = at\hat{\boldsymbol{\imath}} + \boldsymbol{A}\ \cos\omega t\,\hat{\boldsymbol{\jmath}} + \boldsymbol{B}\sin\omega t\,\widehat{\boldsymbol{k}}$

Data Analysis

The quantitative data were analyzed using descriptive statistics, including the mean, median, and standard deviation, to profile students' performance in tabular, graphical, diagrammatic, and mathematical representations. The main function of descriptive statistics is to provide an overall picture of the dataset without making predictive claims or drawing inferences about the broader population from which the sample was taken (Gravetter & Wallnau, 2017). In this study, students' performance was first evaluated using a predefined scoring rubric, after which the outcomes were analyzed descriptively to portray the representational skills of prospective physics teachers.

To examine whether differences existed among the four representation types, a non-parametric statistic Friedman test, was conducted (Sheldon et al., 1996). Given the relatively small sample size, the Friedman test findings were interpreted cautiously and treated as exploratory rather than confirmatory. The purpose of this statistical analysis was to identify tendencies in representational performance rather than to support broad generalizations beyond the studied context.

The interview data were analyzed using thematic analysis following the framework proposed by Clarke & Braun (2017). This approach was selected because it enables systematic identification of recurring patterns in students' representational reasoning and difficulties. The analysis followed six stages. First, all interview recordings were transcribed verbatim and repeatedly read to familiarize the researchers with the data. Second, initial codes were generated inductively by identifying meaningful segments related to students' experiences, representational preferences, and learning challenges. Third, the initial codes were grouped into potential themes that reflected broader patterns of representational difficulties and reasoning strategies. Fourth, the emerging themes were reviewed and refined by comparing them against the original transcripts to ensure internal coherence and consistency. Fifth, themes were defined and named to capture the central meaning of each pattern. Finally, representative excerpts were selected to illustrate each theme and to support the interpretation of the quantitative findings.

To enhance the trustworthiness of the qualitative analysis, several strategies were employed. Peer debriefing was conducted by discussing the coding scheme and emerging themes with a colleague experienced in physics education research. This process helped refine theme definitions and reduce potential researcher bias. In addition, the interview findings were compared with the quantitative results to ensure consistency and methodological triangulation. The qualitative results are therefore intended to provide context-rich, explanatory insights that complement the statistical findings rather than to produce generalizable claims.

Table 1. Test instrument description

Representation	Description	Number
Set A		
Tabular	Given data on an object's position, students can correctly draw conclusions about the object's displacement.	1
Graphical	When presented with a motion graph of an object, students can correctly analyze the object's distance or displacement.	2
Graphical	When presented with a graph of the position-time relationship for several objects, students can correctly infer the objects' speeds.	3
Diagrammatic	When presented with a strobe diagram depicting the motion of two objects, students can correctly compare their speeds.	4
Set B		
Matematical	Solve distance equations as a function of time.	1
Matematical	Formulate the equation of motion as a function of velocity.	2
Set C		
Graphical	Analyze velocity-time graphs.	1

Tabular	Analyze parabolic motion trajectories.	2
Diagrammatic	Calculate position and displacement.	3
Diagrammatic	Given a diagram of the relative motion of a boat and a river current. Represent and interpret a velocity vector diagram to accurately determine the resultant velocity of the boat relative to the shore and the crossing time.	4
Mathematical	Given a particle's position equation as a vector function of time. Represent and manipulate this mathematical equation to accurately determine the velocity and acceleration equations and interpret the geometric meaning of its motion.	5

Source: Set A adapted from Pradana (2021); Set B adapted from Arya (1998); Set C adapted from Giancoli (2013) and Arya (1998).

RESULT AND DISCUSSION

This part of the study reports the outcomes of an examination into how prospective physics teachers employ multiple forms of representation when tackling mechanics problems. The analysis focuses on identifying the specific difficulties they encounter, especially in working with tabular data, graphical displays, diagrammatic images, and mathematical expressions, and explores the broader implications these challenges may hold for the teaching and learning of physics.

Quantitative Findings

The assessment of students' skills in working with multiple representations was conducted using a set of items centered on topics such as linear motion, kinematics, and one-dimensional particle dynamics. Table 2 presents the mean scores and the proportion of accurate responses for each type of representation. At the same time, Figure 1 illustrates these outcomes as a scatter plot showing the percentage of correct answers per item.

The quantitative analysis examined prospective physics teachers' skills across four representational forms: tabular, graphical, diagrammatic, and mathematical. Descriptive statistics indicated noticeable variation in students' performance across these representations. Students achieved the highest mean score in tabular representation (*M = 3.53, SD = 1.55*) followed by mathematical representation (*M = 3.14, SD = 1.54*), diagrammatic representation (*M = 2.56, SD = 0.93*), and graphical representation (*M = 1.67, SD = 1.32*), This pattern indicates that students performed better when working with tables and symbolic mathematical forms than with visual representations. The dominance of the tabular representation is reflected in the large number of maximum scores, suggesting that structured numerical information is relatively easier for participants to interpret. Similarly, the relatively high performance in mathematical representation indicates familiarity with symbolic manipulation and formal mathematical procedures.

Table 2. Descriptive statistics of students' multiple representations score

Representation	N	Mean	Std. Deviation	S.E. Mean	Minimum	Maximum
Tabular	17	3.53	1.55	0.37	0.00	5.00
Graphical	17	1.67	1.32	0.32	0.00	3.33
Diagrammatic	17	2.56	0.93	0.23	1.67	5.00
Mathematical	17	3.14	1.54	0.37	0.00	5.00
Valid N (listwise)	18					
Missing N (listwise)	1					

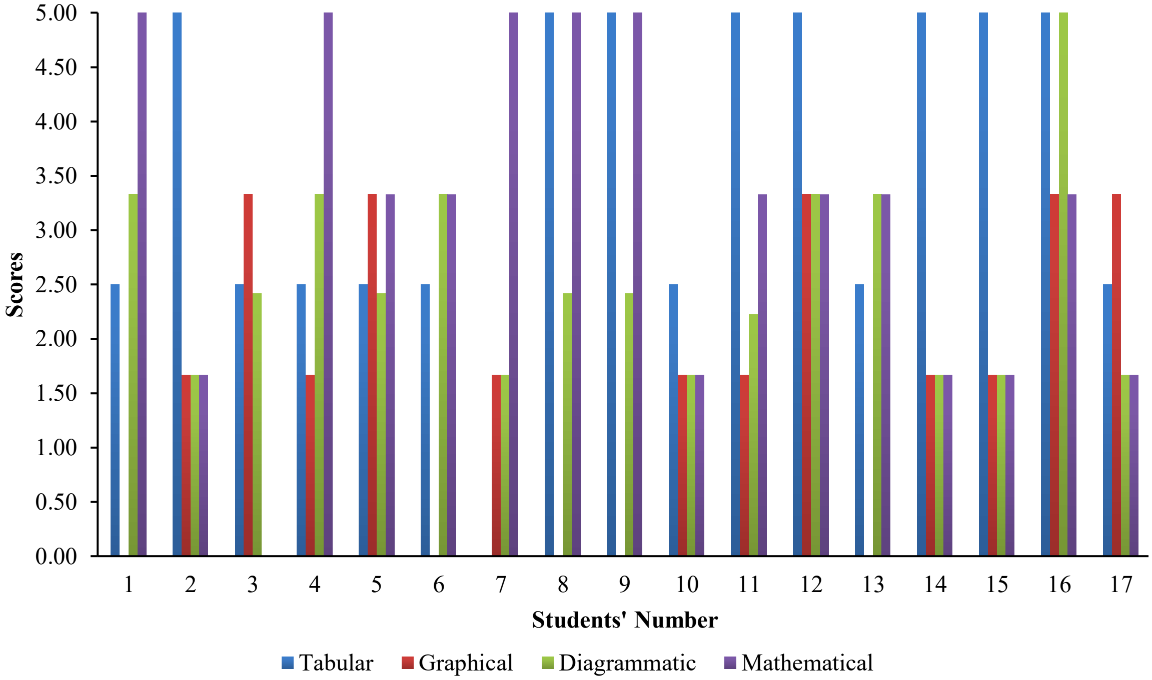


Figure 1. Distribution of scores for each student in each representation

In contrast, the graphical representation shows the lowest average score, with several students obtaining zero and none achieving the maximum score, indicating substantial difficulty in interpreting graphs. The diagrammatic representation occupies a middle position, suggesting moderate ability with schematic or spatial representations, but not at the same level as tabular or mathematical forms. Variation across subjects also reveals differences in representational preferences, with some participants performing well in symbolic tasks but poorly in visual ones, and vice versa. Overall, these findings highlight an imbalance in multiple representation skills, particularly in visual literacy, and suggest the need for instructional emphasis on strengthening students' ability to interpret graphs and translate information across different mathematical representations.

To determine whether these differences were statistically significant, a Friedman test was conducted. The results in Table 3 revealed a statistically significant difference among the four representational forms, X^2 (3) = 8.77, p =033. The mean rank scores in Table 4 further confirmed this pattern, with tabular representation ranking highest (Mean Rank = 0.03), followed by mathematical (2.74), diagrammatic (2.32), and graphical (1.91). These findings indicate that students' multiple representational skills are not balanced across forms. Instead, there is a clear hierarchy of competence, with structured representations such as tables and equations being stronger, and visual-interpretative forms such as graphs being comparatively weaker.

Table 3. Friedman test result

N	17
Chi-square	8.77
df	3
Asymp. Sig.	.033

Table 4. Mean rank of multiple representations

	Mean Rank
Tabular	3.03
Graphical	1.91
Diagrammatic	2.32
Mathematical	2.74

The significantly higher performance in tabular representation suggests that students are more comfortable working with organized numerical data. Tables provide discrete, structured information that allows students to apply procedural reasoning without requiring complex visual interpretation. This aligns with the relatively strong performance observed in mathematical representation, where students rely on formula-based manipulation. In contrast, graphical representation yielded the lowest mean and mean rank scores. This finding indicates substantial difficulty in interpreting visual trends, extracting quantitative relationships, and connecting graphical features with underlying physical concepts. Given the central role of graphs in mechanics, particularly in motion analysis, this weakness is pedagogically concerning. Diagrammatic representation occupied an intermediate position. While students demonstrated some ability to interpret physical situations visually, their performance suggests incomplete integration between diagrams and formal symbolic reasoning. This partial competence reflects a transitional level of representational understanding.

Qualitative Findings

Interviews and responses to open-ended questions provided deeper insight into the challenges prospective physics teachers encounter when working with multiple representations. One of the most frequently mentioned difficulties was the large number of formulas introduced in physics courses. Several students reported that being exposed to numerous equations simultaneously created confusion and cognitive overload, making it difficult to determine which formulas were appropriate in specific problem contexts. As a result, problem solving often began with recalling equations rather than interpreting the physical meaning of the situation.

Another major challenge concerned the interpretation of graphical and diagrammatic representations. Graphs were consistently described as the most demanding representation, particularly when students were required to interpret slopes, identify relationships among variables, and extract quantitative information. Difficulties were also reported in transforming physical situations into diagrams. Students expressed uncertainty about diagrammatic conventions such as vector arrows, scale, and proportional relationships, which often led to incomplete or inaccurate visualizations. Because of these challenges, many students reported relying more heavily on textual or numerical representations instead of visual ones.

In contrast, tabular representations were perceived as more approachable. Students described tables as clear and systematic, allowing them to work with numerical data more confidently. Several participants also emphasized the value of peer discussion and step-by-step explanations in improving their understanding of mechanics concepts. Group discussions were reported to help clarify misunderstandings and support problem solving, while guided explanations made complex material easier to follow.

Further insights emerged regarding students' tendencies to rely on symbolic manipulation as a primary problem-solving strategy. Many participants admitted that they often began by searching for equations rather than first interpreting the physical situation represented visually. This tendency indicates a preference for procedural approaches over conceptual visualization, which may hinder the development of representational coordination skills. As expressed by S5, *"When solving physics problems, I usually start by recalling formulas first. If I can find the equation, I feel more confident, even if I am not completely sure about the graph or the diagram."*

Another recurring theme concerned difficulties in translating information across representations. Students frequently reported that even when they understood individual representations, they struggled to connect them into a coherent understanding of the physical situation. S3 noted, *"I can understand the table or the equation, but sometimes I do not know how to move from the graph to the formula or from the diagram to the equation."*

Similarly, S13 explained, *"I know what the formula means, but I am not always sure how it relates to the motion shown in the diagram."* These statements suggest that the primary challenge lies not only in interpreting single representations but also in coordinating and translating between them.

Students also highlighted the importance of instructional scaffolding in overcoming these challenges. Several participants emphasized that guided practice and repeated exposure to varied representations could gradually improve their confidence. For example, S3 stated, *"If the lecturer shows step-by-step examples and explains how the graph, diagram, and equation are connected, it becomes much easier to follow."* In addition, S3, S5, and S13 reported increased willingness to seek help from peers and noted that peer explanations were easier to understand.

Taken together, the themes identified in the interviews provide a foundation for understanding students' strengths and weaknesses across different representation types. The findings particularly highlight challenges in graphical and diagrammatic representations, procedural reliance on mathematical formulas, and students' preference for structured tabular information. These qualitative insights serve as a basis for the following discussion, which examines each representation type in relation to existing literature and instructional implications.

Understanding the Difficulties with Graphical and Diagrammatic Representations

The results of this study indicate that graphical representation was the weakest area of students' performance, a finding supported by both quantitative and qualitative data. Students reported uncertainty when interpreting slopes, identifying relationships among variables, and extracting quantitative meaning from graphs. These findings are consistent with previous research showing that students often struggle to interpret and use visual representations effectively (Marpaung & Setiawan, 2016; Subali et al., 2015). Working with graphs and diagrams requires the ability to interpret abstract relationships and express them visually, a process that becomes difficult when learners lack a strong conceptual foundation.

Difficulties in graph interpretation may also reflect an incomplete understanding of underlying physics principles or their mathematical expressions. Sezen et al. (2012) found that students' ability to understand graphs is strongly linked to their mathematical skill, particularly in relation to functions and algebra. The present findings reinforce this connection by showing that students frequently convert graphs into equations rather than interpret them directly. This reliance suggests that graphical reasoning has not yet developed into an independent problem-solving tool.

Diagrammatic representation posed similar challenges, particularly when students were required to translate physical situations into spatial visualizations. Many participants expressed uncertainty about diagrammatic conventions such as vector direction, scaling, and proportional relationships. These findings highlight the need for explicit instruction in visual representational literacy within physics teacher education programs.

Mathematical Representation Challenges

Although students performed relatively well in mathematical representation, the qualitative findings reveal that this competence is largely procedural rather than conceptual. Many participants reported beginning problem-solving by searching for formulas, often before interpreting the problem's physical meaning. This pattern indicates an equation-driven strategy that prioritizes symbolic manipulation over conceptual reasoning. Such reliance on formulas may hinder students' ability to connect mathematical expressions with physical phenomena.

Mathematical objects are abstract cognitive constructs that cannot be directly observed, which makes the integration of mathematical reasoning into physics particularly demanding (M.-A. Geyer & Kuske-Janßen, 2019). Students must not only understand formulas but also know when and how to apply them in context. The confusion caused by the large number of formulas suggests that students may lack strategies for selecting and applying appropriate equations. Instructional approaches such as Realistic Mathematics Education have been shown to improve engagement and mathematical representation skills (Maulida et al., 2024), indicating potential directions for improvement.

Preference for Tabular Representations

Students achieved their highest performance in tabular representation, indicating a strong preference for structured numerical data. Tables present information in a systematic, explicit format, reducing cognitive load and enabling students to apply procedural reasoning more easily. Unlike graphs, tables do not require interpretation of trends or relationships, making them more accessible for learners who are still developing representational fluency. This preference suggests that students are more comfortable processing explicitly stated information than inferring relationships from visual data.

Ainsworth (2006) emphasizes that multiple representations support learning by providing complementary perspectives on the same concept. However, these benefits occur only when students can interpret each representation effectively. The present findings suggest that tables may serve as an entry point for developing representational skill. Using tables as scaffolding may help students gradually transition toward more complex visual representations such as graphs and diagrams.

Impact of Collaborative Learning and Worked Examples

The qualitative data also highlight the positive role of collaborative learning and worked examples in supporting students' understanding. Participants reported that group discussions helped them clarify misunderstandings and develop a shared understanding of complex concepts. Collaborative environments allow students to exchange ideas, compare reasoning, and construct knowledge collectively. These findings suggest that peer interaction can play an important role in developing representational skill.

Worked examples were also identified as valuable learning supports. Step-by-step explanations helped students understand the problem-solving process and reduce the cognitive load associated with complex tasks. Such scaffolding can guide students in connecting graphs, diagrams, tables, and equations into a coherent understanding. Incorporating these strategies into physics teacher education may help future teachers develop stronger multiple representational skills.

Implications for Teacher Education

In the process of shifting from one representation to another in physics, students require more than simply transferring data or images in a mechanical manner. There are three principal activities (Figure 2) that should be undertaken to ensure that the act of translation meaningfully supports conceptual understanding (M. A. Geyer & Pospiech, 2019; M.-A. Geyer & Kuske-Janßen, 2019). By following these three activities in sequence, the translation between representations becomes more than a purely technical skill; it evolves into an exercise in conceptual reasoning that actively integrates mathematical forms with the physical realities they are intended to represent.

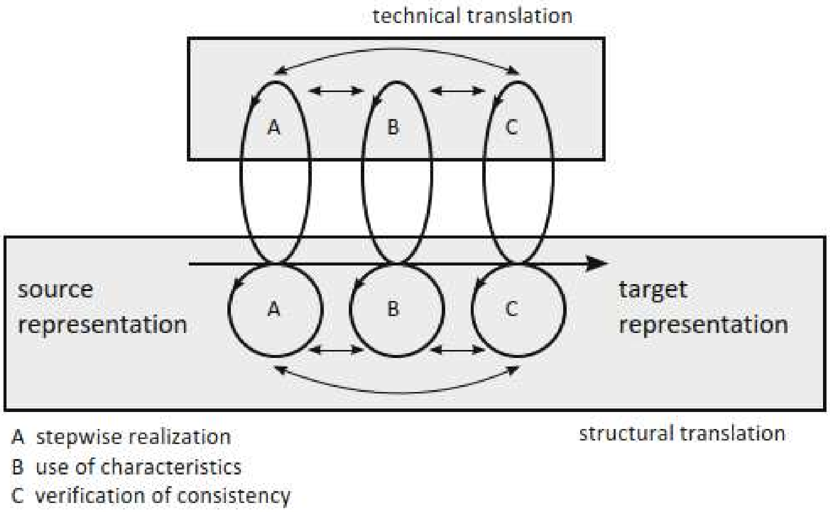


Figure 2. Model of changing between representations of functional dependencies in physics (Geyer & Pospiech, 2019)

The activities A are stepwise realisation. At this point, the representation is broken down into smaller, more manageable parts. For instance, when analyzing a velocity-time graph, students might start by locating the initial point, points of change, and the overall trend of the line before moving on to interpret its physical implications. This method ensures that students have a solid understanding of the essential components of the representation before delving into deeper analysis.

Activity B involves identifying characteristics. In this stage, students focus on identifying specific attributes in the representation that are particularly important. For example, they discover that the slope of a $v - t$ graph indicates acceleration, or that the area under the curve of such a graph represents displacement. By pinpointing these essential characteristics, students can link the visual or numerical elements of the representation to the corresponding physical concepts.

Activity C involves verifying consistency. After producing a new representation, students must assess whether it aligns with established physical principles, experimental results, and the specific features of the problem context. For instance, if a graph shows negative acceleration, students need to check whether this corresponds to the direction of the forces at play or the conditions described. This process prompts learners to move beyond superficial aspects of a representation and instead evaluate its accuracy and conceptual soundness.

The challenges that prospective physics teachers encounter in mastering essential forms of representation pose a considerable concern. As future educators, they are expected to facilitate students' understanding of complex concepts using diverse representational modes (Kind et al., 2017). However, their limitations in this domain may undermine their effectiveness in teaching physics, particularly when conveying abstract ideas that rely heavily on pictorial and mathematical representations.

Addressing these difficulties requires teacher education programs to adopt intentional, structured strategies to enhance representational skills. The curriculum should include explicit training in representational practices, emphasizing the importance of engaging with multiple forms and offering targeted instruction to foster these skills, with representation-based learning serving as a promising alternative (Amelia et al., 2024). Equally important is integrating mathematics and physics education to ensure that future teachers can apply mathematical concepts seamlessly in physics contexts, thereby fostering a more coherent and conceptually robust understanding. Furthermore, the deliberate use of technology and visual tools (such as simulations and interactive graphics) should be incorporated into teacher preparation to support comprehension and make abstract ideas more accessible (Nikat et al., 2021). Through these efforts, teacher education programs can better equip future physics teachers with the representational skills needed to enhance student learning and encourage deeper conceptual engagement.

Limitations of the Study

As an exploratory case study conducted within a single institutional context, this study should be interpreted in light of several limitations. First, the relatively small sample size ($N = 17$), drawn from a single public university, restricts the statistical power of the analysis and limits the generalizability of the findings beyond the studied context; therefore, the results should be viewed as exploratory. Second, although the assessment instrument underwent expert validation, it may not fully capture the complexity of representational skill, particularly students' ability to coordinate and translate among graphical, diagrammatic, tabular, and mathematical representations. Finally, the qualitative data were based on a small number of semi-structured interviews and self-reported responses, which may be subject to response bias and do not allow for full triangulation through classroom observations or performance-based measures. Consequently, the findings should be interpreted as context-specific insights rather than as a general profile of prospective physics teachers.

Recommendations for Future Research

Future studies should involve larger, more diverse samples from multiple institutions to improve the generalizability of the findings and enable more detailed analysis of variation in representational skill across contexts. Longitudinal research is also needed to examine how prospective physics teachers' representational skills develop throughout their training and early teaching experiences. In addition, intervention-based studies should investigate the effectiveness of instructional strategies, such as explicit multiple-representation training, technology-supported learning, and collaborative problem-solving. Such research would provide stronger empirical evidence to guide the design of physics teacher education programs aimed at improving representational skill.

■ CONCLUSION

This study examined the multiple representational skills of 17 prospective physics teachers in a specific institutional context. The findings provide context-bound insights into patterns of representational strengths and challenges rather than a generalizable profile. The findings revealed statistically significant differences across representation types, with students demonstrating the highest proficiency in tabular representations, followed by mathematical representations, then diagrammatic representations. In contrast, graphical representations showed the lowest performance. Qualitative analysis further revealed persistent challenges in interpreting graphs, visualizing physical concepts, and selecting and applying appropriate mathematical equations. Collaborative learning, worked examples, and explicit representational training emerged as promising strategies to address these weaknesses. These findings highlight the importance of explicitly integrating multiple-representation training into physics teacher education programs, strengthening the connection between mathematics and physics, and incorporating technology-enhanced and collaborative learning approaches. Developing balanced representational skills is essential for future teachers to communicate physics concepts effectively and to support students' conceptual understanding and problem-solving skills.

However, these conclusions should be interpreted with caution. The study was conducted with a relatively small sample of 17 students from a single public university, which limits the generalizability of the findings beyond the studied context. Therefore, the results should be viewed as exploratory and indicative rather than representative of prospective physics teachers more broadly. Future studies involving larger and more diverse samples across institutions are needed to confirm and extend these findings. Expanding the scope of research will provide a stronger empirical basis for designing instructional strategies to improve representational skills in physics teacher education.

■ DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the writing of this manuscript, the authors used ChatGPT to assist with language refinement/proofreading. The authors have reviewed and edited the content generated by this tool and assume full responsibility for the content of the published article.

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