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The role of spatial ability in high school students' understanding of molecular geometry

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Abstract
Molecular geometry is one of the biggest challenges in science education. Since molecular structures exist at a microscopic level, students often struggle to visualize them in three dimensions (3D), making it difficult to understand concepts such as bond angles, molecular shapes, and electron pair interactions. This study explores the role of spatial ability in high school students' understanding of molecular geometry. Using a quantitative descriptive method, the study examined the spatial ability and molecular science comprehension of 58 high school students. Data were collected using standardized tests, including the Mental Rotation Test (MRT), shape assembly, and 3D visualization for spatial ability, along with a molecular science comprehension test focusing on VSEPR theory. The results obtain that students' spatial ability is significantly low, with average scores falling far below expected standard. The results suggest the need for more effective teaching strategies that incorporate 3D visualization tools to enhance students' ability. Future research should focus on interactive learning approaches, such as virtual simulations to help students better visualize molecular structures and improve their understanding of science concepts.

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1. Introduction

Understanding molecular geometry structure presents a big challenge in science education. Molecular structures exist on a microscopic scale, making them difficult for students to visualize accurately. Traditional teaching methods often use on two-dimensional (2D) representations found in textbooks, which fail to capture the three-dimensional (3D) nature of molecules. Limitation of the method often leads to misconceptions about molecular geometry, bonding interactions, and chemical properties. The difficulty in visualizing molecular structures is not only experienced by students but also presents a challenge for teachers in effectively teaching the abstract concepts (Lohning et al., 2019; Abdinejad et al., 2020).

One of the key factors understanding molecular geometry is spatial ability. Spatial ability refers to the cognitive skill that allows individuals to manipulate, rotate, and visualize objects in three-dimensional space. In the context of science, this skill is crucial for conceptualizing molecular shapes, predicting bond angles, and understanding how molecular structures effect the reactivity and function. Strong spatial skills enable students to visualize from 2D molecular representations to 3D structures. This ability enables them to get concepts such as bond hybridization, molecular polarity, and electron pair repulsion with greater accuracy (Ardian et al., 2021). If the students with low spatial ability struggle to visualize two-dimensional into three-dimensional structural model, leading to confusion in identifying molecular geometry and predicting molecular interactions. Studies have shown that students with weak spatial reasoning skills tend to rely heavily on memorization rather than conceptual understanding. As a result, they often develop misconceptions, such as misinterpreting molecular bond angles or failing to recognize the impact of lone pairs on molecular shape. This difficulty becomes more complicated when students encounter complex molecules with multiple atoms and varied geometric configurations (Fatemah et al., 2020; Wang et al., 2022).

Importance of spatial ability in science education, it is necessary to implement teaching strategies that enhance students' visualization skills. Previous research many discusses about visualization method through three-dimensional for enhancing students' spatial ability (Dickmann et al., 2019; Coan et al., 2020; Fatemah et al., 2020; Savchenkov, 2020). Discussing about analyzing SWOT from cheminformatics method for increasing concept of molecular lesson (Pernaa, 2022). Discussing about additional instruction in Learning process Molecular for enhancing the concept (Ping, 2022; Ninkovic & Adamov, 2023). Discussing about correlation between spatial ability and students' gender (Yang, et al., 2024). Many researches were discussing for enhancing the concept molecular with students' spatial ability. There is no discussion analyzing about the role of spatial ability for understanding the molecular concept.

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The study aims to evaluate students' spatial ability levels and investigate their impact on understanding molecular geometry concepts. This research will identify common learning difficulties associated with low spatial ability and propose effective instructional strategies to enhance students' spatial reasoning in science education. The findings of this study are expected to provide insights into the role of spatial ability in learning and inform the development of more effective, visualization-based teaching methods.

2. Method

This study follows a quantitative descriptive method to explore high school students' spatial ability and its relation between spatial ability with the understanding of molecular geometry concepts, particularly in visualizing molecular structures. The research focuses on observing and analyzing existing data to identify role students' spatial abilities and their understanding of molecular geometry.

The study consists 58 high school students at 10th Grade. The students divide into 2 class, which are class A and B. The data involve standardized development assessments by Paul Newton and Helen Bristoll in Spatial Ability Practice Test 1 to measure spatial ability and molecular geometry comprehension. Further that, study also involves assessment of VSEPR Theory to test students' spatial ability test to visualize and manipulate in three-dimensional (3D) chemical molecular geometry. This test included key components: the Mental Rotation Test (MRT), which evaluated students' ability to recognize rotated shapes, shape assembly, which determining set of shapes can be combined to form a given shape, and 3D visualization, which identifying flat shape (two-dimensional) into a molecular geometry (three-dimensional). The test consisted of 50 multiple-choice questions, with students given 60 minutes to complete it.

The test consists of different types of spatial ability questions, each focusing on specific spatial skills. The questions can be categorized as follows by Table 1.

Table 1. Distribution of question numbers and category

Question numbers	Category	Description
1-25	Mental Rotation	Identifying identical shapes from two different groups, where some shapes may be rotated
26-30	Rotation Identification	Selecting the rotated version of a given shape from multiple answer choices
31-35	Shape assembly	Determining which set of shapes can be combined to form a given shape
36-39	3D visualization	Identifying which flat shape can be folded into a specific cube
40-50	Visualization of chemical molecular geometry	Determining which form/shape of each chemical molecules in 3D

Questions for evaluating students' spatial ability in every category.

2. The shapes in Group 1 and Group 2 are identical, although some of them may be rotated. *
Which shape in Group 2 corresponds to the shape number 2 corresponds to the shape in Group 1?

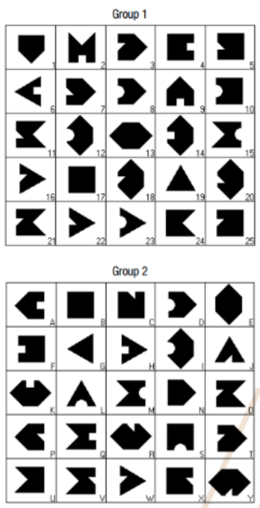

Figure 1. The question for mental rotation

26. Which figure is identical to the first? *

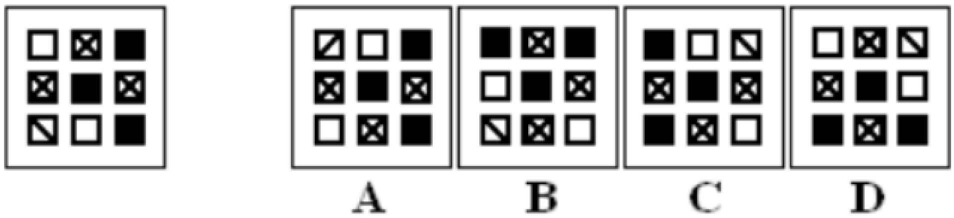

Figure 2. The question for rotation identification

31. Which group of shapes can be assembled to make the shape shown? *

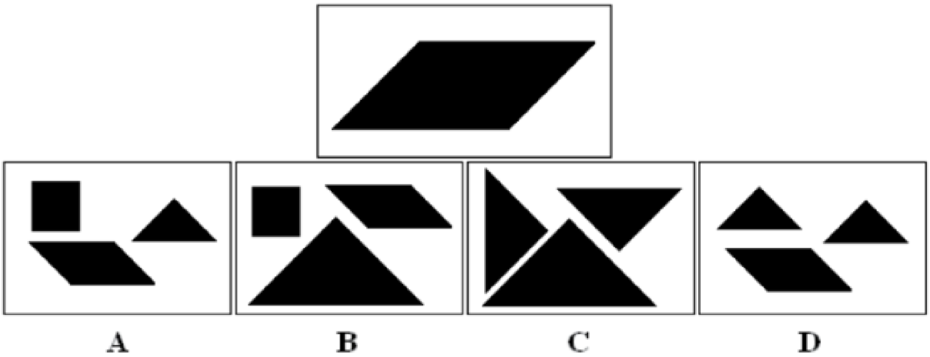

Figure 3. The question for shape assembly

36. Which of the following cube net that suitable with cube? *

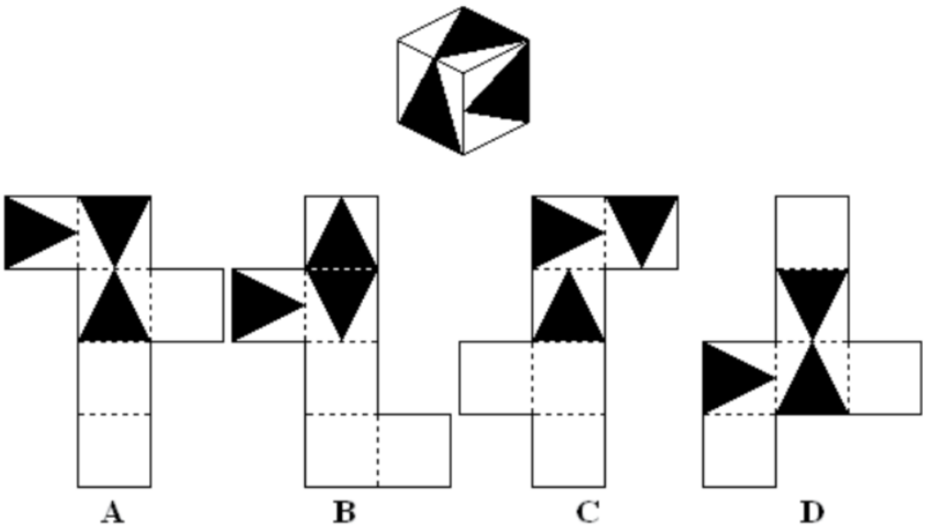

Figure 4. The question for 3D visualization

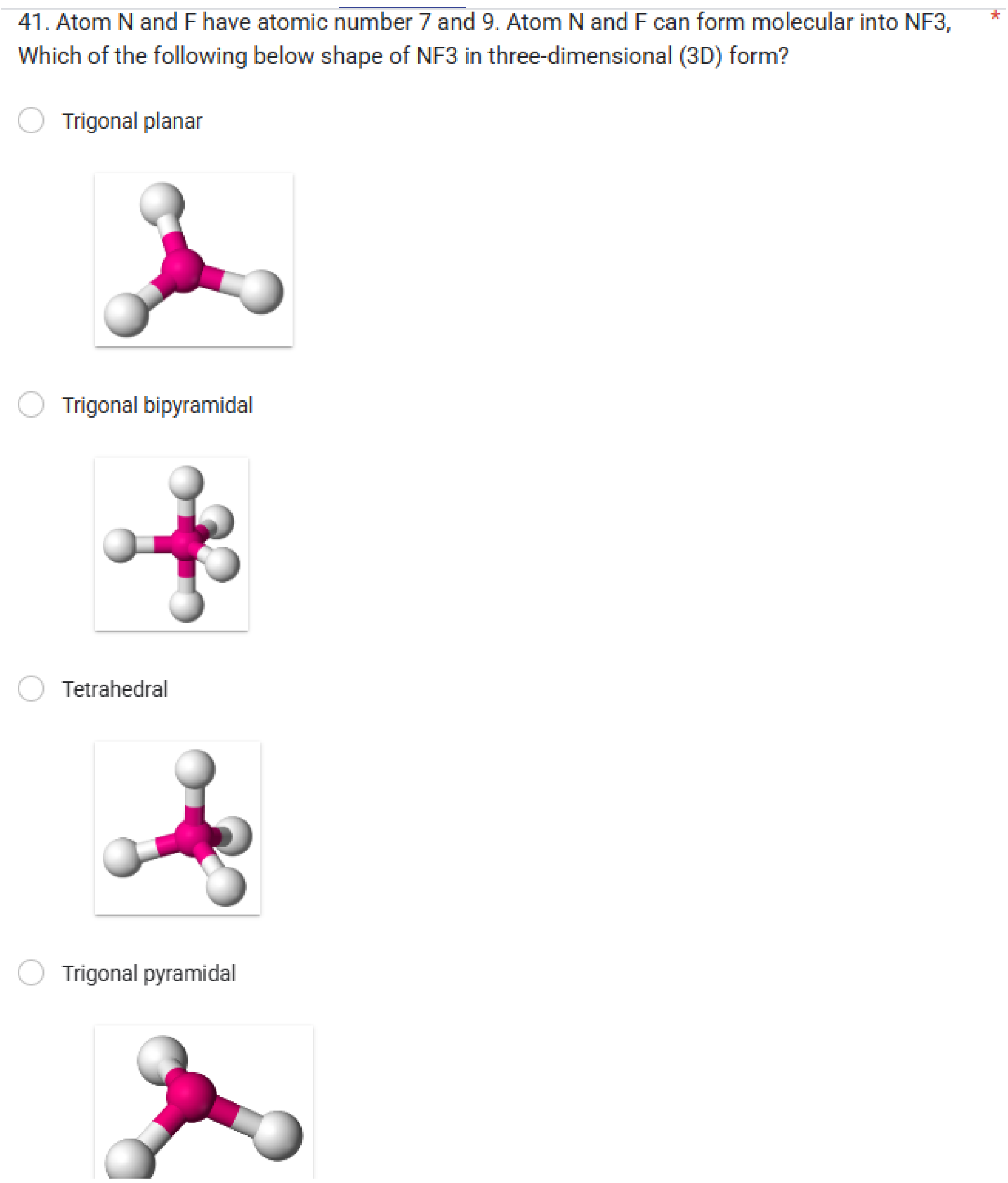

Figure 5. Visualization of chemical molecular geometry

The research was carried out in three main stages. The preparation stage involved selecting test instruments from prior studies and coordinating with schools to organize test sessions. The data collection stage took place in a controlled environment where students completed the test separately to ensure accuracy and minimize external influences. Finally, in the data analysis stage, descriptive statistical methods were used to examine the distribution of students' spatial ability scores.

3. Results and Discussion

3.1. Students' Spatial Ability in Understanding Molecular Geometry

The result of study indicates that the spatial ability of students in understanding molecular geometry is considerably low. Spatial ability is a fundamental cognitive skill that enables individuals to mentally visualize and manipulate three-dimensional objects, which is essential in the field of chemistry, Science. Molecular geometry, in particular, requires students to understand how atoms are arranged in three-dimensional space and how different molecular structures affect chemical properties. Without adequate spatial ability, students may struggle with interpreting molecular diagrams, predicting molecular shapes, and understanding structural relationships between atoms.

A total of 58 students in this study divided into two classes: Class A with 29 students and Class B with 29 students. The students were assessed using a standardized spatial ability test using Paul Newton and Helen Bristoll Spatial ability Practice Test 1 designed to measure their ability to mentally manipulate and visualize molecular structures. The results obtained from these assessments are presented in Table 2, which shows the average spatial ability scores of students in each class.

Table 2. Average spatial ability scores of students

Class	Total Students	Average Score
A	29	18.71
B	29	21.24

The data presented in Table 2 show that students' spatial ability class A obtaining an average score of 16.21 and class B obtaining an average score of 21.24. These scores suggest that the majority of students have serious difficulties in mentally visualizing molecular structures, which may hinder their understanding of molecular geometry and chemical bonding concepts.

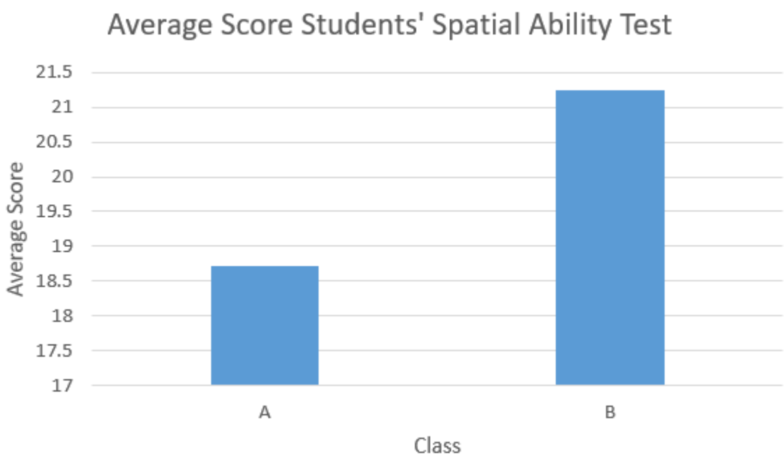

Figure 6. Average Score Students' Spatial Ability Test

The results from the spatial ability test, as shown in Figure 1, reveal a noticeable difference between the two classes. Class B performs slightly higher than class A. Although the difference is not extreme, it suggests that students in Class B may have stronger spatial reasoning skills compared to those in Class A.

The results highlight an important challenge—students' overall spatial ability remains relatively low. Since spatial skills play a crucial role in visualizing molecular structures, these results raise concerns about how well students can grasp three-dimensional molecular geometry concepts. Prior research has shown that students with stronger spatial skills tend to perform better in subjects that require mental manipulation of objects. The fact that both classes scored below what is typically considered a strong spatial ability range suggests that many students struggle with these types of tasks.

3.2. Score Distribution and Classification of Students' Spatial Ability

The distribution graph of students' scores in both classes is presented in Figure 7. This figure illustrates the average score, median, and score range for students in both groups. The average score represents the total sum of all students' scores divided by the number of students. This measure is useful for comparing students' performance with classifications from previous research. The median score indicates the middle value of all test scores, providing insight into the central tendency of students' performance. The score range highlights the interval between the highest and lowest scores, helping to analyze variations in students' spatial ability within the test.

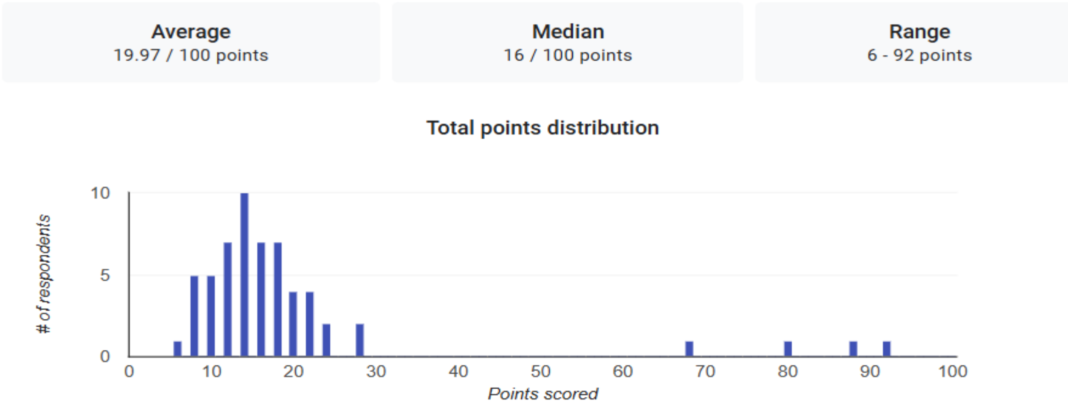

Figure 7. The Distribution of Students' Spatial Ability Score

Figure 7 explains about most of the students' score in range 0-30 while they were answering the development spatial ability test. The median is 16/100. The score interval from 6 – 92. The lowest score is 6 and the highest score is 92. Figure 2 indicates the level most of the students in spatial ability are low.

Further that, the students' spatial ability average score compares with Rahman, et al. 2022 research that have developed thresholds for very low until very high spatial ability scores, which can serve as a benchmark for evaluating the students' performance in this study. Table 3 presents these classification levels based on findings from previous research.

Table 3. Spatial Ability Classification

Interval Score	Category
87-100	Very high
80-83	High
73-77	Above the average
60-70	Average
53-57	Below the average
47-50	Low
0-43	Very low

By comparing the average spatial ability scores in Table 2 with the classification in Table 3, it is evident that students in this study fall far below the lowest threshold defined by previous research. In studies conducted by Rahman, et al. 2022, students with scores below 40 were categorized as having low spatial ability. However, the highest average score obtained in this study was only 21.24, which is significantly lower than the lowest threshold for spatial ability in previous research.

The results indicate that students in this study exhibit extremely low spatial ability compared to expected standards. The implications of this are significant, as spatial ability is a key skill in science, especially chemistry that allows students to visualize molecular structures, predict molecular shapes, and understand three-dimensional molecular interactions. Students who lack adequate spatial ability may struggle to mentally rotate molecules, interpret molecular diagrams, and comprehend structural differences between isomers. This may lead to misconceptions about molecular geometry, difficulties in applying VSEPR theory, and an inability to predict the behavior of molecules based on their spatial arrangement.

Several studies have highlighted the importance of spatial ability in chemistry learning, particularly in topics such as molecular geometry, and chemical bonding. Research conducted by Guspatni et al. (2020) and Widarti et al. (2022) has shown that students with higher spatial ability tend to perform better in chemistry compared to those with lower spatial ability. The ability to mentally manipulate molecular structures allows students to develop a deeper understanding of molecular shape, hybridization, and electron pair repulsion.

3.3. The Problem and Effect on Low Students' Spatial Ability

Students with low spatial ability, such as those in this study, are likely to face several difficulties in understanding molecular geometry in Table 4.

Table 4. The Problem and Effect on Low Students

No	Problem	Effect
1	Difficulty in interpreting molecular diagrams	Students struggle to translate 2D textbook representations into 3D molecular geometry
2	Challenges in predicting molecular shapes	Students are hard applying VSEPR Theory to determine bond angles and electron pair arrangement
3	Misconceptions about molecular structure	Students lead to incorrect predictions about molecular interactions and geometry

Table 4 shows several key challenges that students face due to their low spatial ability, which significantly impacts their understanding of molecular geometry. One of the primary difficulties is the interpretation of molecular diagrams. Many students struggle to translate 2D textbook representations into accurate 3D molecular structures, making it harder for them to visualize spatial relationships between atoms. This issue directly affects their ability to mentally manipulate molecular models, a skill that is crucial for comprehending chemical structures. Another major challenge is predicting molecular shapes using the VSEPR (Valence Shell Electron Pair Repulsion) Theory. Students with low spatial ability often struggle to determine bond angles and the arrangement of electron pairs, leading to errors in shape prediction. This difficulty suggests that traditional teaching approaches relying on static diagrams may not be sufficient for developing students' spatial reasoning skills. Additionally, misconceptions about molecular structure further complicate learning. Students with weak spatial skills tend to misinterpret molecular interactions and geometry, which can result in fundamental errors when predicting molecular behavior. These misconceptions highlight the need for alternative instructional strategies, such as interactive 3D models, molecular visualization software, and hands-on activities, to help students build a stronger conceptual understanding of molecular shapes. On the other hand, students with higher spatial ability tend mastering in these areas, as they can easily manipulate 3D molecular models in their minds, allowing them to understand molecular symmetry, understand resonance structures, and predict shapes outcomes more accurately.

The result of this study suggests an urgent need for intervention strategies to help students develop better spatial skills. Several studies have proposed effective teaching approaches to enhance students' spatial visualization and molecular reasoning skills. One approach is the integration of three-dimensional molecular visualization tools, such as computer-based modeling software (Fatemah et al., 2020; Smith et al., 2020). These tools allow students to interact with molecular models in real-time, helping them develop a more intuitive understanding of molecular structures. In addition, physical molecular models, such as Molymod kits, have been shown to improve students' ability to visualize molecular geometry by allowing them to manually build and manipulate 3D molecular structures (Demir, 2022). Another effective method is the implementation of spatial training exercises in chemistry education. The students who engaged in spatial reasoning exercises, such as mental rotation tasks and visualization drills, showed significant improvements in their spatial ability. By incorporating such training into Science, especially for chemistry lessons, students may develop stronger molecular visualization skills, leading to improved performance in topics related to molecular geometry.

4. Conclusion

This study reveals that students' spatial ability remains low, as reflected in their test scores. Many students face difficulties in visualizing three-dimensional (3D) structures, which impacts their ability to grasp concepts such as predicting molecular shapes. Compared to previous research, the spatial ability scores in this study are significantly lower, indicating an ongoing challenge in mentally interpreting molecular models. Furthermore, instruction should incorporate more engaging and interactive tools. The use of 3D visualization tools, such as computational molecular modeling software, augmented reality (AR), and physical model kits, can help students better conceptualize molecular geometry. These tools allow learners to explore structures dynamically rather than relying on static textbook diagrams. The 3D visualization tools can support the development of students' spatial skills. Future research should focus on evaluating the effectiveness of these strategies in classroom settings to enhance conceptual understanding and student engagement in science learning.

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All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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