



Diagnosing Molecular Geometry Misconceptions Using a Two-Tier Diagnostic Test Based on Visual-Spatial Indicators

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ABSTRACT

Purpose - This study aimed to diagnose students' conceptual understanding and misconceptions in molecular geometry using three visuospatial indicators: molecular symmetry planes, mental rotation, and interpretation of 3D-to-2D representations.

Methodology - A descriptive quantitative design was employed with 54 eleventh-grade students. Data were collected using a six-item two-tier diagnostic test, with two items representing each visual-spatial indicator. The instrument was reviewed by six experts using a five-point Likert scale and analyzed using Aiken's V. Internal consistency was examined using dichotomously scored Tier 1 and Tier 2 responses. In contrast, the combination of the two tiers was used for diagnostic classification. Responses were classified into Conceptual Understanding, Misconception, and No Conceptual Understanding.

Findings - The instrument obtained an overall Aiken's V of 0.89, indicating adequate content validity across content relevance, two-tier construction, language and readability, and visual representation. The internal consistency coefficient was low ($\alpha = 0.41$). Diagnostic analysis showed that Conceptual Understanding ranged from 7.41% to 31.48%, with the highest proportion in 3D-to-2D interpretation and the lowest in mental rotation. Misconceptions were highest in mental rotation (50.93%), followed by molecular symmetry planes (44.44%) and interpretation of 3D-to-2D representations (38.89%). Item-level analysis revealed difficulties in identifying reflection planes from molecular orientation, maintaining three-dimensional relationships during mental rotation, distinguishing mental rotation from reflection, integrating wedge-dash notation with tetrahedral structure, and distinguishing changes in visual representation from changes in molecular geometry.

Contribution - This study contributes a visual-spatial perspective to two-tier diagnostic assessment by linking students' misconception patterns to specific visual-spatial indicators, providing targeted information to understand and address conceptual difficulties in molecular geometry.

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INTRODUCTION

Chemistry is a discipline that requires students to understand abstract concepts that cannot be directly observed. Consequently, meaningful chemistry learning depends on students' ability to construct and connect multiple representations of chemical phenomena, including symbolic, submicroscopic, and macroscopic representations (Phajan et al., 2025). Among various chemistry topics taught at the secondary school level, molecular geometry is consistently recognized as one of the most cognitively demanding because students are required to visualize the three-dimensional arrangement of atoms, predict molecular shapes based on electron-pair repulsion, and interpret spatial relationships that are commonly presented through two-dimensional representations (Ramadhan et al., 2025; Rahmawati et al., 2021). These representational demands make molecular geometry particularly challenging for many learners and often lead to conceptual misunderstandings.

Understanding molecular geometry extends beyond memorizing the names of molecular shapes. Students must construct accurate mental representations of molecular structures, mentally manipulate these representations from different perspectives, and relate symbolic diagrams to their corresponding three-dimensional configurations. This process requires strong visual-spatial ability, which refers to the cognitive capacity to perceive, manipulate, transform, and interpret spatial information mentally (Kiernan et al., 2021). In chemistry learning, visuospatial ability enables students to rotate molecular models mentally, recognize spatial orientations, identify molecular symmetry, and translate two-dimensional structural representations into three-dimensional mental models (Winata, 2023). When these cognitive processes are insufficiently developed, students are more likely to develop misconceptions rather than simply experience temporary learning difficulties (Kuit & Osman, 2021).

Numerous studies have demonstrated the important role of visual-spatial ability in chemistry education. Students with well-developed visual-spatial ability tend to interpret molecular structures more accurately, predict bond angles more consistently, and construct scientifically acceptable representations of molecular geometry (Salame & Kabir, 2022). Conversely, students with limited spatial ability often have difficulty connecting two-dimensional molecular diagrams to their corresponding three-dimensional structures, leading to incorrect reasoning during problem solving (Vanzal & Dwiningsih, 2023). These findings indicate that misconceptions in molecular geometry should be viewed not only as conceptual errors but also as manifestations of limitations in students' visuospatial cognitive processing.

The theoretical importance of visual-spatial ability is closely associated with the concept of multiple chemical representations. According to the framework of chemical representation, meaningful understanding of chemistry requires students to establish coherent relationships among macroscopic phenomena, submicroscopic particle behavior, and symbolic representations (Langitasari & Robandi, 2023; Talanquer, 2022). In learning molecular geometry, these representational levels are reflected in Lewis structures, the Valence Shell Electron Pair Repulsion (VSEPR) model, and three-dimensional molecular structures. Rather than functioning as independent representations, these models complement one another in explaining molecular shape and molecular behavior (Alharbi, 2025). Consequently, students must continuously translate information across different representational levels to develop scientifically accurate conceptual understanding.

The process of translating between representational levels requires more than factual knowledge; it requires active visual-spatial reasoning. Students are expected to infer three-dimensional molecular structures from two-dimensional Lewis structures, mentally rotate molecules, and recognize symmetry elements that are not always directly observable. Previous studies have shown that students frequently experience difficulties in coordinating multiple chemical representations, which subsequently contributes to conceptual misunderstanding (Kapici, 2023). Failure to perform these representational transformations often results in hidden misconceptions, in which students can select correct answers but rely on scientifically incorrect reasoning. Such misconceptions are difficult to identify through conventional assessments because correct responses do not necessarily reflect correct conceptual understanding (Talanquer, 2022). This importance has

also been highlighted in recent research on chemistry education, which demonstrated that integrating three-dimensional molecular visualizations can effectively strengthen students' spatial visualization and conceptual understanding of molecular geometry (Saputra & Dwiningsih, 2025).

Despite the importance of visual-spatial processing in molecular geometry, misconceptions concerning this topic remain prevalent among secondary school students. Many students approach molecular geometry by memorizing molecular shapes without fully understanding the spatial reasoning underlying VSEPR theory (Stiawan et al., 2022). Because molecular geometry requires students to visualize three-dimensional molecular structures, effective learning depends on adequate visuospatial processing (Habiddin et al., 2023). However, classroom instruction at the senior high school level continues to rely predominantly on static two-dimensional representations, providing limited opportunities for students to actively construct and manipulate three-dimensional molecular models (Rohmah & Hidayah, 2022). This mismatch between instructional representations and the cognitive demands of molecular geometry increases the likelihood of persistent misconceptions.

Previous studies have addressed this problem from different perspectives. One line of research has focused on improving students' conceptual understanding through visualization media, augmented reality, virtual simulations, and other technology-supported learning environments, which have consistently been shown to enhance students' visual-spatial ability (Permana et al., 2023; Fombona-Pascual et al., 2022). Another line of research has employed two-tier diagnostic tests to identify misconceptions by examining both students' answers and their reasoning (Hasanah et al., 2023; Mardiyanningsih et al., 2023). These approaches have provided important contributions to chemistry education. However, they have generally been developed independently, leaving limited attention to how specific visual-spatial processes contribute to different misconception patterns in molecular geometry.

This limitation is particularly important because visual-spatial ability is not a single cognitive construct. Understanding molecular geometry requires students to perform different spatial processes, including mental rotation, representational translation, and recognition of molecular symmetry. Difficulties in these processes may lead to misconceptions that conventional assessments focused solely on answer correctness cannot adequately identify. Moreover, the presence of a correct answer does not necessarily indicate scientifically sound reasoning when students fail to coordinate the visual-spatial processes required to construct molecular representations. Therefore, a diagnostic approach that considers both conceptual responses and the visuospatial processes underlying them is needed to provide a more comprehensive account of students' misconceptions.

In response to this problem, the present study integrates visual-spatial ability and misconception diagnosis into a single diagnostic framework. Previous studies have generally examined visual-spatial ability as a predictor of students' learning achievement or investigated the effectiveness of instructional media in improving spatial skills (Permana et al., 2023; Pratamadita & Dwiningsih, 2022), whereas other studies have employed two-tier diagnostic tests to identify misconceptions and students' mental models across various chemistry topics (Mardiyanningsih et al., 2023). By bringing these two perspectives together, this study proposes a diagnostic framework that links students' responses to a two-tier diagnostic test with three visual-spatial ability indicators: mental rotation, interpretation of 3D-to-2D representations, and molecular symmetry planes. Unlike conventional diagnostic assessments that primarily classify students by their level of conceptual understanding, the proposed framework offers a more comprehensive interpretation by linking students' reasoning patterns to the specific visuospatial processes involved in constructing molecular representations. Consequently, misconceptions are not only identified but also interpreted in light of the underlying cognitive characteristics that contribute to their formation. This approach contributes to the development of diagnostic assessment in chemistry education by providing empirical evidence to support more targeted instructional planning and strengthen educational measurement and evaluation practices in science learning.

The present study was conducted with eleventh-grade senior high school students because molecular geometry is formally introduced at this educational level, where students are expected to transition from

concrete operational thinking to more abstract reasoning (Rahmawati et al., 2021). At this stage, students must mentally construct and manipulate three-dimensional molecular representations, making them particularly vulnerable to misconceptions when visual-spatial reasoning is insufficiently developed. Therefore, identifying misconceptions at this stage is essential to support timely instructional interventions before they become deeply entrenched.

Based on the background, problem, and research gap described above, this study addresses the following research questions: (1) What are the profiles of students' visual-spatial ability based on the indicators of mental rotation, interpretation of 3D-to-2D representations, and molecular symmetry planes in constructing molecular representations? (2) How is students' conceptual understanding distributed across the three visual-spatial ability indicators? Moreover, (3) What misconception patterns are revealed through students' reasoning in the two-tier diagnostic test?

Accordingly, this study aims to diagnose students' misconceptions in molecular geometry using a two-tier diagnostic test based on indicators of visual-spatial ability. Specifically, the study seeks to: (1) identify students' visual-spatial ability profiles based on the indicators of mental rotation, interpretation of 3D-to-2D representations, and molecular symmetry planes; (2) analyze the distribution of students' conceptual understanding across each visual-spatial indicator; and (3) identify students' misconception patterns by examining the reasoning underlying their responses in the two-tier diagnostic test. The findings are expected to provide empirical evidence to inform the development of more comprehensive diagnostic assessment instruments and to support chemistry teachers in designing instructional strategies that address students' specific visual-spatial learning difficulties in molecular geometry.

METHODOLOGY

Research Design

This study employed a quantitative approach with a descriptive research design to investigate students' conceptual understanding and misconception patterns in molecular geometry based on three visual-spatial indicators. A descriptive quantitative design was selected because the study aimed to describe the distribution of students' responses and identify patterns of conceptual understanding and misconceptions across predetermined visual-spatial indicators without applying an instructional intervention (Creswell, 2012).

The diagnostic framework was developed by relating each molecular geometry task to a specific visual-spatial process. Mental rotation refers to the ability to mentally manipulate the orientation of a three-dimensional molecular structure from different viewpoints. Interpretation of 3D-to-2D representations refers to the ability to translate spatial information encoded in a three-dimensional molecular structure into an appropriate two-dimensional representation. Molecular symmetry planes refer to the ability to recognize reflection relationships within a three-dimensional molecular structure. The framework was used to examine not only whether students selected correct answers but also whether their explanations reflected scientifically appropriate spatial reasoning.

Participant

The participants were 54 eleventh-grade students from two classes at SMA Kemala Bhayangkari 1 Surabaya, Indonesia. Purposive sampling was used because the participants had completed instruction on molecular geometry and the prerequisite concepts of chemical bonding and Lewis structures. Data collection was conducted during the even semester of the 2025/2026 academic year on May 19, 2026. Each class was allocated 2 × 40 minutes to complete the diagnostic test.

Because the participants were recruited from two classes within a single school, the findings are interpreted within the context of the participating students. They are not intended to represent the broader population of senior high school students. Students' responses were treated confidentially and were used solely for research purposes.

Data Collection

Data collection was conducted through four sequential stages: problem identification, instrument development, expert validation and revision, and data collection. First, relevant literature on molecular geometry, visual-spatial ability, chemical representations, and misconceptions was reviewed to establish the theoretical basis and identify the research gap. Second, a test blueprint was developed by mapping molecular geometry content onto three visual-spatial indicators: molecular symmetry planes, mental rotation, and interpretation of 3D-to-2D representations. The two-tier diagnostic items and scoring guidelines were then developed based on the blueprint.

Third, the developed instrument was reviewed by six validators, comprising three chemistry education lecturers and three experienced senior high school chemistry teachers. The instrument was revised based on the validation results before being administered to the participants. Finally, the validated diagnostic test was administered individually to 54 eleventh-grade students who had completed instruction on molecular geometry. Students were instructed to select an answer in Tier 1 and provide the corresponding reasoning in Tier 2. The six items were completed within the allocated classroom time of 2×40 minutes. Students' Tier 1 and Tier 2 responses were recorded as the primary data. Permission to conduct the research was obtained from the participating school, and students' responses were treated confidentially and used solely for research purposes.

Instrument

Two instruments were used in this study: a two-tier diagnostic test and an expert validation sheet. The diagnostic test consisted of six items, with two items representing each of the visual-spatial indicators: mental rotation, interpretation of 3D-to-2D representations, and molecular symmetry planes. Each item consisted of two tiers: Tier 1 assessed students' conceptual responses, and Tier 2 assessed their underlying reasoning. The two-tier structure was adapted from Treagust (1988), and the combined responses were classified into Conceptual Understanding, Misconception, and No Conceptual Understanding.

The expert validation sheet was completed by six validators, consisting of three chemistry education lecturers and three experienced senior high school chemistry teachers. Each item was evaluated using a five-point Likert scale (1–5) across 26 criteria grouped into four aspects: content validity (10 criteria), two-tier test construction (6 criteria), language and readability (5 criteria), and visual quality and representation (5 criteria). These criteria assessed the alignment of the items with the intended visual-spatial processes, the quality of the two-tier structure and reasoning elicitation, language clarity, and the accuracy and appropriateness of the visual representations. The research instruments are summarized in Table 1.

Table 1. Research Instruments and Indicators

Instrument	Purpose	Indicators	Example Item	Scale
Two-Tier Diagnostic Test	To diagnose students' conceptual understanding and patterns of misconceptions in molecular geometry.	Mental rotation; interpretation of 3D-to-2D representations; molecular symmetry planes.	Molecular representation and reasoning about its spatial characteristics.	Two-tier
Validation Sheet	To assess the validity and diagnostic suitability of the two-tier diagnostic test.	Content relevance, visual-spatial alignment, construct, and diagnostic suitability.	Assessment of item relevance, visual representation, and reasoning elicitation.	Likert 1–5

Data Analysis

Instrument validity was evaluated using Aiken's V (Aiken, 1985). The 26 validation criteria were rated by six experts using a five-point Likert scale. The criteria covered four aspects: content validity, two-tier test construction, language and readability, and visual quality and representation. Aiken's V coefficients were

calculated for each criterion and summarized across the four aspects. A coefficient ≥ 0.75 was used as the criterion for acceptable content validity (Azwar, 2012).

Because the diagnostic test employed a two-tier structure and was designed to represent three distinct visual-spatial indicators, reliability was assessed with respect to the instrument's function as a diagnostic assessment rather than as a unidimensional scale. Tier 1 and Tier 2 responses were scored dichotomously (1 = correct and 0 = incorrect) and examined for response consistency. The combination of the two tiers was then used for diagnostic classification rather than treated as a single continuous score. Therefore, the reliability coefficient was interpreted as supplementary evidence of response consistency and was not used as the sole criterion for assessing the diagnostic instrument's adequacy.

Students' responses were subsequently classified according to the combination of Tier 1 and Tier 2 responses, adapted from Ardianti et al. (2021), as shown in Table 2.

Table 2. Student Understanding Categorization Criteria

Tier 1	Tier 2	Category
Correct	Correct	Conceptual Understanding
Correct	Incorrect	Misconception
Incorrect	Correct	Misconception
Incorrect	Incorrect	No Conceptual Understanding

For each item, each student contributed one response. Because two items were used for each visual-spatial indicator, each indicator yielded 108 responses (54 students $\times$ 2 items). Therefore, the percentage for each category at the indicator level was calculated as:

$$P = \frac{f}{N} \times 100\% \quad (1)$$

where P is the percentage of responses in a particular category, f is the number of responses classified into that category, and N is the total number of responses for the corresponding indicator (N = 108).

This response-based aggregation was used because two diagnostic items were included for each visual-spatial indicator. Accordingly, the percentages reported at the indicator level represent the distribution of responses across the two items, rather than the percentage of unique students.

In addition to the quantitative classification, students' Tier 2 explanations were analyzed descriptively at the item level. Responses categorized as misconceptions were examined to identify recurring reasoning patterns. Each reasoning pattern was compared with the scientifically accepted explanation for the corresponding molecular geometry concept and grouped according to the visual-spatial process required by the item. This analysis was used to distinguish specific misconception patterns related to molecular symmetry, mental rotation, and interpretation of 3D-to-2D representations. Generative AI tools were used to assist with language editing, grammar improvement, and manuscript readability during the writing process.

FINDINGS

Instrument Validity and Reliability

The two-tier diagnostic test was evaluated by six validators using a five-point Likert scale. The validation criteria consisted of 26 items covering content validity, two-tier test construction, language and readability, and visual quality and representation. The Aiken's V coefficients for the four aspects are presented in Table 3.

Table 3. Aiken's V Coefficients by Validation Aspect

Validation Aspect	Number of Criteria	Mean Aiken's V	Interpretation
Content Validity	10	0.90	Valid
Two-Tier Test Construction	6	0.90	Valid
Language and Readability	5	0.88	Valid
Visual Quality and Representation	5	0.90	Valid
Overall	26	0.89	Valid

All four validation aspects exceeded the predetermined criterion of 0.75, with an overall Aiken's V of 0.89. The highest coefficient was obtained for visual quality and representation ($V = 0.90$), followed by content validity and two-tier test construction ($V = 0.90$), while language and readability obtained the lowest coefficient ($V = 0.88$). These results indicate that the instrument demonstrated adequate content relevance, appropriate two-tier construction, acceptable language and readability, and suitable visual and representational quality for the intended diagnostic purpose.

Internal consistency was examined using the dichotomously scored Tier 1 and Tier 2 responses. When the 12-tier responses were treated as a conventional single scale, Cronbach's alpha was 0.41, indicating low internal consistency. This result was interpreted cautiously because the six diagnostic items were distributed across three distinct visual-spatial indicators and were designed primarily for diagnostic classification rather than measurement of a single homogeneous construct.

Distribution of Conceptual Understanding Across Visual-Spatial Ability Indicators

Data from 54 students were analyzed across six two-tier diagnostic items, with two items per visual-spatial ability indicator. Thus, each indicator yielded 108 responses ($54 \text{ students} \times 2 \text{ items}$). Responses were classified into three categories based on the combination of Tier 1 and Tier 2 responses: Conceptual Understanding (C-C), Misconception (C-I and I-C), and No Conceptual Understanding (I-I). The distribution of these categories across the three indicators is presented in Table 4.

Table 4. Distribution of Conceptual Understanding Categories Across Visual-Spatial Ability Indicators

Visual-Spatial Ability Indicator	Conceptual Understanding (%)	Misconception (%)	No Conceptual Understanding (%)
Molecular Symmetry Planes	19.44	44.44	36.11
Mental Rotation	7.41	50.93	41.67
Interpretation of 3D-to-2D Representations	31.48	38.89	29.63

The proportion of responses classified as Conceptual Understanding ranged from 7.41% to 31.48% across the three visual-spatial ability indicators. The highest proportion of Conceptual Understanding was found for the interpretation of 3D-to-2D representations (31.48%), whereas the lowest proportion was observed for mental rotation (7.41%). The Misconception category accounted for the largest proportion of responses in both mental rotation (50.93%) and molecular symmetry planes (44.44%). For the interpretation of 3D-to-2D representations, 38.89% of responses were classified as Misconception, followed by Conceptual Understanding (31.48%) and No Conceptual Understanding (29.63%).

The No Conceptual Understanding category accounted for 41.67% of responses for mental rotation, 36.11% for molecular symmetry planes, and 29.63% for the interpretation of 3D-to-2D representations. Overall, the combined proportion of responses classified as Misconception or No Conceptual Understanding was highest for mental rotation (92.60%), followed by molecular symmetry planes (80.55%) and interpretation of 3D-to-2D representations (68.52%).

Item-Level Response Patterns and Misconceptions

To obtain a more detailed picture of students' reasoning, responses to Tier 1 and Tier 2 were analyzed at the item level. Each item consisted of five Tier 2 explanation options, comprising one scientifically appropriate explanation and four distractors representing different patterns of incorrect reasoning. The response patterns for each visual-spatial ability indicator are presented below (Figure 1).

For Item 1, which assessed the molecular symmetry of BF_3 , 46.30% of students selected the correct Tier 1 answer, whereas only 27.78% selected the scientifically appropriate Tier 2 explanation. Among the responses associated with the correct Tier 1 choice, 18.52% selected Tier 2 explanation 5, which associated the symmetry of BF_3 with rotational symmetry rather than identifying the molecular plane itself as a reflection plane (oh). Explanation 2 was selected by 27.78% of students and represented the interpretation of a horizontal plane

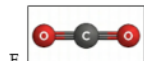
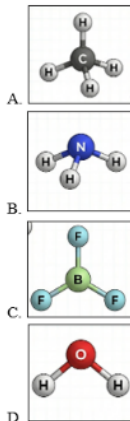
primarily as a visual division between the upper and lower parts of the molecular representation. Explanation 3 was selected by students who associated the presence of a reflection plane with the requirement that an atom located on the plane must have a corresponding paired atom.

Molecular Symmetry Planes (Items 1 and 2)

Item 1

The following molecule that possesses a horizontal plane of symmetry (a plane dividing the molecule into two mirror-image top and bottom halves, where the plane is perpendicular to the principal axis) is...

Tier 1:



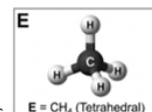
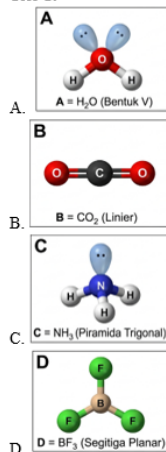
Tier 2 (Reason):

1. All atoms lie in a single plane, such that the regions above and below the plane possess identical counterparts.
2. The molecule can only be divided into left and right sections, meaning it does not form mirror-image pairs in the vertical (top-bottom) direction.
3. Atoms above and below the plane lack corresponding counterparts, so the condition for horizontal symmetry is not met.
4. The molecule possesses lone electron pairs that disrupt symmetry between the top and bottom regions relative to the plane under consideration.
5. The molecule exhibits symmetry only upon rotation; thus, it lacks the symmetry that would be demonstrated through a planar reflection operation.

Item 2

Consider the following molecular models. The molecule with the highest degree of symmetry, such that it appears equivalent after multiple rotations is ...

Tier 1:



Tier 2 (Reason):

1. The molecule possesses multiple axes of rotation and planes of symmetry, appearing equivalent from various directions.
2. The molecule appears symmetrical only when viewed from a specific direction due to the uneven arrangement of atoms.
3. Lone pairs of electrons reduce the degree of symmetry by influencing the spatial distribution around the central atom.
4. Atomic positions cannot be interchanged via symmetry operations because each atom occupies a distinct location.
5. Planar molecules always exhibit the highest degree of symmetry because all atoms lie within a single plane.

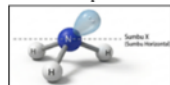
Figure 1. Items 1–2: Molecular Symmetry Planes

For Item 2, which assessed the molecular symmetry of CO₂, 53.70% of students selected the correct Tier 1 answer, while only 22.22% selected the scientifically appropriate Tier 2 explanation. Another 22.22% selected explanation 5, which interpreted molecular symmetry in terms of the molecule appearing identical from every viewing direction. Other response patterns included explanation 2, which linked the presence of a symmetry plane to the possibility of molecular distortion during mental rotation, and explanation 3, which reflected an incorrect interpretation of the role of lone pairs in determining molecular symmetry.

Mental rotation (Items 3 and 4)

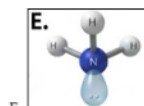
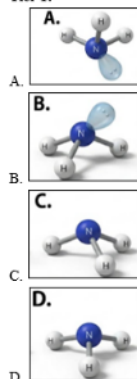
Item 3

Observe the following 3-dimensional molecular shapes:



If the molecule is rotated 180° about the X-axis passing through the N atom, the correct resulting molecular orientation is ...

Tier 1:

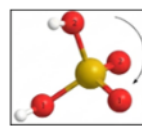


Tier 2 (Reason):

1. A 180° rotation about the X-axis swaps the top and bottom positions but does not change the left and right positions in the image.
2. A 180° rotation about the X-axis changes nothing because NH₃ possesses threefold symmetry in its molecular arrangement.
3. A 180° rotation about the X-axis swaps the left and right positions because both directions change relative to the axis of rotation.
4. A 180° rotation about the X-axis produces the same configuration as a 90° rotation about the Y-axis for the molecule.
5. A 180° rotation about the X-axis swaps the H atom at the front with the H atom at the back, as well as the top and bottom positions.

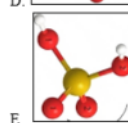
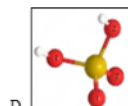
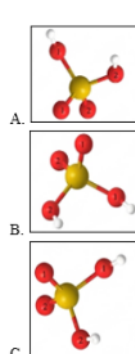
Item 4

Observe the following 3-dimensional molecular shapes:



Which is the result of a 90° clockwise rotation?

Tier 1:



Tier 2 (Reason):

1. A 90° clockwise rotation shifts the orientation such that the right side moves to the bottom and the top side moves to the right.
2. A 90° clockwise rotation swaps the left and right positions, resulting in an inverted image orientation.
3. An L-shape lacks 90° rotational symmetry; therefore, the image's orientation changes following the rotation.
4. A 90° clockwise rotation produces a mirror image, altering the molecular arrangement to resemble a reflection.
5. A 90° clockwise rotation results in an L-shape with its long arm pointing upwards.

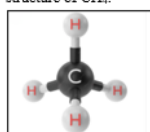
Figure 2. Items 3–4: Mental Rotation

For Item 3, 38.89% of students selected the correct Tier 1 answer, and 24.07% selected the correct Tier 2 explanation. Explanation 1 was selected by 14.81% of students, representing a response pattern in which the effect of a 180° mental rotation about the X-axis was considered in terms of changes in the upper-lower position without accounting for the associated change in front-back orientation. Explanation 4 was selected by 16.67% of students. It represented the interpretation that mental rotations involving different axes and angles, such as 180° about the X-axis and 90° about the Y-axis, could result in the same molecular orientation.

For Item 4, 72.22% of students selected the correct Tier 1 answer, but only 14.81% selected the correct Tier 2 explanation. Explanation 2 was selected by 14.81% of students, reflecting an interpretation of a 90° mental rotation as reversing the left-right arrangement, analogous to a reflection. Explanation 4 was selected by 3.70% of students and was associated with the production of a mirror image.

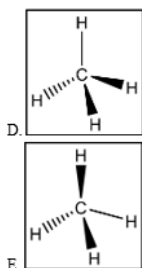
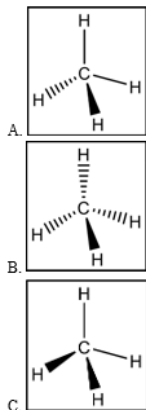
Interpretation of 3D-to-2D Representations (Items 5 and 6)

Item 5
Observe the following 3D molecular structure of CH_4 :



Based on the 3D molecular shape above, the most appropriate 2D shape for CH_4 is...

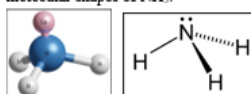
Tier 1:



Tier 2 (Reason):

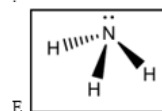
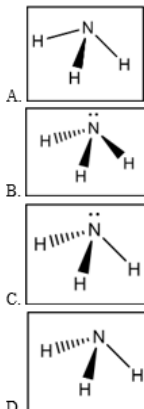
1. The wedge-dash representation depicts atoms extending out of the plane of the drawing with a thick line and those extending behind the plane.
2. All hydrogen atoms in CH_4 lie in a single plane, allowing all bonds to be drawn using standard lines.
3. In a tetrahedral shape, two bonds can appear within the plane, while one extends toward the viewer and another extends behind the plane of the drawing.
4. Dashed lines are used to specifically and consistently indicate bonds extending behind the plane of the drawing.
5. The tetrahedral shape of CH_4 cannot be represented in two dimensions without losing information regarding its spatial orientation.

Item 6
Observe the following 3D and 2D molecular shapes of NH_3 :



If the molecule is viewed from the opposite direction (from the back side of the molecule), then the correct representation is ...

Tier 1:



Tier 2 (Reason):

1. Viewing from the opposite side makes the atom that was originally in front appear to be in the back, causing the wedge and dash to swap positions.
2. Wedge-dash notation applies only to perfect tetrahedral molecules; therefore, it is not used for other molecular shapes.
3. Changing the viewing angle does not affect the spatial orientation of the atoms, so the front and back positions appear unchanged.
4. All atoms in NH_3 lie in a single plane, so depth indicators are unnecessary in a two-dimensional representation.
5. Changing the direction of observation alters only the visual orientation, not the fundamental shape of the molecule being observed.

Figure 3. Items 5–6: Interpretation of 3D-to-2D Representations

For Item 5, which assessed the interpretation of wedge-dash notation in CH_4 , 35.19% of students selected the correct Tier 1 answer. The largest proportion of students (48.15%) selected Tier 2 explanation 1. Although this explanation reflected an understanding of the basic function of wedge and dash symbols in indicating spatial depth, it did not provide the scientifically appropriate justification for why configuration A represents the tetrahedral structure of CH_4 most accurately. Within the two-tier diagnostic framework used in this study, this response was classified as a misconception because the explanation did not adequately connect the representation of depth with the overall three-dimensional tetrahedral arrangement. Only 11.11% of students selected the designated correct Tier 2 explanation.

For Item 6, which assessed changes in the viewpoint of an NH_3 molecular representation, 68.52% of students selected the correct Tier 1 answer, whereas only 7.41% selected the correct Tier 2 explanation. Explanation 4 was selected by 11.11% of students and represented the interpretation of NH_3 as a planar molecule in which all atoms occupy the same plane. Explanation 3 was selected by 9.26% of students. It reflected the interpretation that the relative positions of atoms with respect to the observer remain unchanged when the molecule is viewed from a different direction. Explanation 5 was selected by 3.70% of students and represented the interpretation that changing the observer's viewpoint changes the actual molecular geometry rather than only its visual representation.

DISCUSSION

Conceptual Understanding of Molecular Geometry Across Visual-Spatial Ability Indicators

The findings reveal substantial differences in students' conceptual understanding across the three visual-spatial ability indicators. Only 7.41%–31.48% of responses were classified as Conceptual Understanding, whereas the combined proportions of Misconception and No Conceptual Understanding were considerably higher. The most pronounced difficulty was observed in the mental rotation indicator, for which only 7.41% of responses demonstrated Conceptual Understanding, while 92.60% were classified as Misconception or No Conceptual Understanding. In contrast, the highest proportion of Conceptual Understanding was observed for the interpretation of 3D-to-2D representations (31.48%), although difficulties still predominated for this indicator.

This pattern indicates that students' difficulties with molecular geometry vary with the type of visuospatial processing required. Molecular symmetry and spatial transformations require learners to coordinate visual information with abstract geometric operations, whereas interpretation of a 2D representation may initially rely on familiar representational conventions. Research on molecular symmetry has shown that identifying symmetry elements requires students to manipulate molecular structures mentally, and that a molecule's orientation can influence such reasoning within the representation (Crandell & Pazicni, 2022). Similarly, Thayban et al. (2022) found a positive relationship between spatial ability and success in understanding molecular symmetry. These findings provide a basis for interpreting the variation among indicators in the present study.

A particularly important pattern is the discrepancy between Tier 1 correctness and Tier 2 reasoning. On several items, the proportion of students selecting the correct answer was substantially higher than that selecting the scientifically appropriate explanation. The discrepancy was most pronounced in Item 4, where 72.22% of students selected the correct Tier 1 answer. However, only 14.81% selected the correct Tier 2 explanation, and for Item 6, the corresponding proportions were 68.52% and 7.41%, respectively. This pattern suggests that selecting the correct answer may overestimate students' conceptual understanding when the reasoning supporting the answer is not examined. A two-tier diagnostic format is therefore useful for distinguishing answer recognition from scientifically coherent conceptual reasoning.

Visual Anchoring in Understanding Molecular Symmetry Planes

The response patterns for BF_3 and CO_2 indicate that students frequently relied on the visual orientation of molecular representations when reasoning about symmetry. In Item 1, several responses associated a horizontal symmetry plane with a visual division between the upper and lower portions of the representation, while other responses connected molecular symmetry to rotational symmetry or to the presence of paired atoms. In Item 2, some students interpreted symmetry as the molecule appearing identical from every viewing direction rather than as preservation of the molecular structure under a specific symmetry operation.

These patterns are consistent with the role of molecular orientation in shaping students' activation of symmetry knowledge. Crandell & Pazicni (2022) found that changes in molecular orientation affected which symmetry resources students activated when identifying rotational and reflection symmetry elements. Their findings suggest that students may possess relevant knowledge but activate it inconsistently depending on the molecule's visual context. More specifically, Crandell & Pazicni (2024) reported that students' identification of reflection planes varied across representations, highlighting the challenge of connecting the visual arrangement of a molecular model with the underlying geometric definition of a symmetry operation.

The present findings, therefore, suggest that some students may be anchoring their reasoning to surface visual features rather than to invariant geometric relationships. This interpretation is also consistent with Ramadhan et al. (2025), who found that spatial ability was positively related to students' success in understanding molecular symmetry. Their findings indicate that success in symmetry tasks is not independent of learners' ability to process three-dimensional spatial information.

From an instructional perspective, this pattern is important because students may appear to know the definition of a symmetry plane yet apply it based on the orientation of a particular diagram. Molecular symmetry instruction, therefore, needs to support students in recognizing that the underlying symmetry relationship remains unchanged when the same molecule is viewed or represented from different orientations. The exploration-based molecular symmetry activity developed by recent research further demonstrates the usefulness of manipulating 2D figures and 3D molecular models to help students construct symmetry concepts through operations rather than relying solely on verbal definitions.

Mental Rotation and Confusion Between Spatial Transformations

The mental rotation indicator produced the highest proportion of misconceptions (50.93%) and the lowest proportion of Conceptual Understanding (7.41%). The item-level response patterns reveal at least two forms of difficulty. The first concerns the mental manipulation of three-dimensional molecular structures. In Item 3, some students accounted for the apparent change along one spatial dimension but did not account for the simultaneous change in another dimension. Such responses suggest that students may be processing the visible motion of molecular components without maintaining the full three-dimensional spatial relationships during the transformation.

This interpretation is consistent with current research indicating that mental rotation entails transforming visual objects while preserving relevant spatial relationships. Stewart et al. (2022) demonstrated that mental object rotation can require observers to infer and transform three-dimensional structure from two-dimensional visual information. In chemistry education, spatially complex molecular tasks similarly require learners to coordinate multiple spatial relations rather than focus on a single visible change.

The second difficulty concerns the distinction between mental rotation and reflection as different spatial transformations. In Item 4, 72.22% of students selected the correct Tier 1 answer, yet only 14.81% selected the correct Tier 2 explanation. Some responses interpreted mental rotation as producing a mirror image, suggesting that the final visual appearance may have been recognized without a corresponding understanding of the operation that generated it. The distinction is conceptually important because mental rotation and reflection represent different geometric transformations. When students identify transformations primarily from their visual outcomes, different operations may appear equivalent even though they involve different changes in spatial relationships. The present findings, therefore, suggest that the difficulty with mental rotation is not limited to mental manipulation itself; it also involves the ability to discriminate among different types of transformations.

This interpretation is relevant to research on chemistry learning that emphasizes the interaction between spatial reasoning and representational competence. Thayban et al. (2022) demonstrated the contribution of spatial ability to understanding molecular symmetry, while Habiddin et al. (2023) showed that students' activation of symmetry knowledge depends partly on the representational context. Together, these findings support the view that successful reasoning about molecular transformations requires both spatial processing and appropriate interpretation of the representation.

The relatively high proportion of No Conceptual Understanding responses also warrants attention because this category may reflect difficulties that precede the formation of a stable alternative conception. In the molecular symmetry and mental rotation items, students who selected incorrect responses in both tiers may have lacked the foundational spatial schema needed to interpret the molecular structure or the transformation being presented. For molecular symmetry, this may reflect insufficient understanding of the geometric relationship between a molecule and a reflection plane rather than a specific alternative conception. In mental rotation, the I-I pattern may indicate difficulty constructing or maintaining a three-dimensional mental representation before performing the required spatial transformation. Thus, No Conceptual Understanding should not be interpreted simply as an absence of factual knowledge; in this study, it may also indicate an insufficient foundation for coordinating molecular representations with the visual-spatial operations required by the task.

Interpreting 3D Molecular Structures from 2D Representations

The interpretation of 3D-to-2D representations produced the highest proportion of Conceptual Understanding among the three indicators. Nevertheless, the item-level results reveal a considerable gap between recognizing an appropriate representation and explaining the structural information it encodes.

For Item 5, the most frequently selected Tier 2 response (48.15%) indicated that students recognized the basic function of wedge and dash symbols in representing spatial depth. However, this explanation did not provide the scientifically appropriate justification for why configuration A most accurately represents the tetrahedral structure of CH_4 . Within the diagnostic framework of this study, this response was classified as a misconception because students treated the meaning of the individual depth symbols as sufficient justification for selecting the molecular configuration, without integrating those symbols with the overall three-dimensional arrangement.

Thus, the misconception identified in this item does not represent a complete misunderstanding of wedge-dash notation. Rather, it reflects an incomplete integration of representational information. Students recognized what the symbols communicate, but did not adequately coordinate this information with the overall tetrahedral structure. Recent work on students' difficulties with wedge-dash structures similarly highlights the importance of understanding how graphical conventions encode three-dimensional chemical information rather than simply recognizing the symbols themselves. This finding can also be understood in the broader context of representational competence. Kiernan et al. (2024) emphasized that chemical representations are not merely illustrations but tools for reasoning, and that learners must understand what information a representation makes available as well as how that information should be interpreted. In molecular geometry, this means that a wedge or dash should not be interpreted as an isolated symbol; its meaning must be coordinated with the spatial arrangement of the complete molecular structure.

For Item 6, the discrepancy between Tier 1 and Tier 2 performance was even more pronounced: 68.52% of students selected the correct Tier 1 answer, whereas only 7.41% selected the scientifically appropriate Tier 2 explanation. Several distractor patterns indicate difficulty distinguishing a change in representation from a change in molecular structure. The interpretation of NH_3 as planar also points to difficulty connecting the molecular representation with the three-dimensional structure predicted by the molecular geometry model.

Such difficulties are consistent with recent research on molecular geometry and students' coordination of multiple representations. Yamtinah et al. (2026) identified conceptual errors in molecular geometry, spatial perception, and transitions between two- and three-dimensional representations using a two-tier diagnostic test. Their findings are particularly relevant because they demonstrate that students may experience conceptual difficulties not only with molecular geometry itself but also with the relationship between different representational forms.

Similarly, Erlina et al. (2024) found that students can develop alternative conceptions about molecular structure when they have difficulty connecting different perspectives and representations. They showed that molecular geometry cards and model-building activities can help students reconstruct more scientifically appropriate understandings.

The present findings, therefore, reinforce the importance of treating molecular representations as objects of reasoning rather than merely as visual aids. Students need to understand that a change in viewing direction changes the appearance of a representation without changing the underlying molecular structure. Developing this distinction may be particularly important for students who can identify the correct representation but cannot explain the spatial relationship that it encodes.

Instrument Reliability and Its Interpretation

The low internal consistency coefficient ($\alpha = 0.41$) should be interpreted cautiously in the context of the diagnostic design. The instrument consisted of six diagnostic items distributed across three distinct visual-spatial indicators, with two items per indicator. In addition, the Tier 1 and Tier 2 responses were designed to capture complementary aspects of students' conceptual responses and reasoning rather than to form a single

homogeneous scale. Therefore, the low coefficient indicates limited internal consistency when the 12-tier responses are treated as a single conventional scale. However, it does not, by itself, invalidate the instrument's diagnostic function. Nevertheless, the result highlights the need for caution when interpreting the items as a single quantitative measure. It supports item- and indicator-level diagnostic analyses in this study.

Study Limitations

This study has several limitations that should be considered when interpreting the findings. First, the participants comprised 54 students from two classes at a single senior high school, which limits the transferability of the findings to students at other schools or in other educational contexts. Second, each visual-spatial indicator was represented by only two diagnostic items. This limited item coverage may not fully capture the breadth of each visual-spatial process. It may also contribute to the relatively low internal consistency observed for the instrument as a whole. Third, the study employed a descriptive-diagnostic design without an instructional intervention; therefore, the findings identify patterns of students' difficulties but do not establish the effectiveness of particular instructional strategies for addressing them. These limitations should be considered when interpreting the diagnostic profiles and when comparing the findings with those from larger or more diverse student populations.

Instructional Implications

The identified response patterns provide specific implications for instruction in molecular geometry by targeting the visual-spatial processes associated with each diagnostic indicator. For molecular symmetry planes (Items 1 and 2), the instruction should move beyond identifying symmetry from a single molecular orientation and emphasize the geometric relationships among the reflection plane, the molecular structure, and the symmetry operation. For example, students can be presented with the same BF_3 and CO_2 structures in multiple orientations and asked to identify the reflection plane in each representation. Students can then manipulate physical or virtual molecular models to verify whether reflection across the proposed plane preserves the molecular arrangement. This activity can help students distinguish a reflection plane from a visual dividing line and from rotational symmetry, addressing the response patterns observed in Items 1 and 2. Such exploratory manipulation of molecular representations is consistent with research emphasizing the role of molecular orientation in students' activation of symmetry knowledge (Crandell & Pazicni, 2024).

For mental rotation (Items 3 and 4), instruction should explicitly distinguish mental rotation from reflection and provide structured opportunities for students to track changes across multiple spatial dimensions. A possible activity is to present a molecular model in an initial orientation, specify a rotation angle and axis, and ask students to predict the new positions of selected atoms, then compare their predictions with a physical or virtual model. Students can be required to explain changes in front-back, left-right, and upper-lower relationships to ensure that the complete three-dimensional transformation is considered. This approach directly addresses the difficulties observed in Items 3 and 4, particularly the tendency to interpret rotation as a simple reversal or as the production of a mirror image. The use of manipulable molecular representations can help students coordinate spatial transformations with molecular structure (Stiawan et al., 2022).

For the interpretation of 3D-to-2D representations (Items 5 and 6), the instruction should explicitly connect graphical conventions with the complete three-dimensional molecular structure. For Item 5, students can construct a tetrahedral CH_4 model and then identify or draw the corresponding wedge-dash representation from different viewing directions. They should explain how wedges, dashes, and ordinary lines encode spatial depth and how these symbols function together to represent the tetrahedral arrangement. For Item 6, students can examine NH_3 models from different viewpoints and compare the resulting two-dimensional representations, explaining why a change in viewpoint does not alter the underlying molecular geometry. These activities can help students distinguish changes in visual representation from changes in molecular structure and strengthen coordination among multiple representations (Kiernan et al., 2024; Erlina et al., 2024).

Overall, the findings support instructional strategies that explicitly coordinate molecular models, spatial transformations, and two-dimensional representations rather than treating these components independently. The substantial discrepancy between Tier 1 and Tier 2 performance further indicates that instruction should require students not only to select an answer but also to explain the spatial reasoning underlying their choice. Such explanation-based activities can provide opportunities for teachers to identify whether students' difficulties reflect misconceptions, incomplete coordination of representations, or insufficient conceptual foundations. Consequently, the two-tier diagnostic results can be used to design targeted instructional responses for specific visual-spatial difficulties in molecular geometry.

Suggestions for Future Research

Future research should involve larger, more diverse samples from multiple schools to examine whether the diagnostic patterns identified in this study are consistent across educational contexts. Further studies should also expand the number of items for each visual-spatial indicator to obtain a broader representation of the constructs and improve the stability of reliability estimates. In addition, intervention-based studies could investigate whether instruction incorporating physical or virtual molecular models, structured mental-rotation activities, and explicit 3D-to-2D representation tasks can reduce the misconception patterns identified in the present study. Future research may also combine two-tier diagnostic assessment with interviews or think-aloud protocols to obtain more detailed evidence of the reasoning underlying responses indicating No Conceptual Understanding and Misconception.

CONCLUSION

This study demonstrated that a two-tier diagnostic test based on visual-spatial indicators can provide differentiated information about students' conceptual understanding and misconceptions in molecular geometry. The instrument demonstrated strong evidence of content relevance and adequacy of its two-tier construction, language, and visual representation based on expert validation, with an overall Aiken's V of 0.89. The diagnostic results showed that students' difficulties varied across the three visual-spatial indicators, with mental rotation showing the highest proportion of misconceptions and the lowest proportion of conceptual understanding. The discrepancies between Tier 1 responses and Tier 2 reasoning further demonstrated the importance of examining students' explanations rather than relying on answer correctness alone. The findings can inform targeted instruction through the use of manipulable molecular models for symmetry and mental rotation, structured activities for distinguishing rotation from reflection, and explicit tasks linking wedge-dash representations and changes in viewpoint to three-dimensional molecular structures. However, the findings should be interpreted within the limitations of the study, particularly the use of 54 students from two classes in a single school and only two diagnostic items for each visual-spatial indicator. Future research should involve larger, more diverse samples, increase the number of items per indicator, and combine two-tier assessment with interviews or think-aloud protocols and intervention-based studies to examine underlying reasoning and evaluate instructional approaches to reduce the identified misconceptions.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

Generative AI tools were used to assist with language editing, grammar improvement, and readability during manuscript preparation. The authors reviewed and verified all AI-assisted outputs and remain fully responsible for the accuracy, originality, interpretation, and final content of the manuscript.

REFERENCES

- Aiken, L. R. (1985). Three Coefficients for Analyzing the Reliability and Validity of Ratings. *Educational And Psychological Measurement*, 45(1), 131-142. <https://doi.org/10.1177/0013164485451012>

- Alharbi, A. A. (2025). Cognitive Learning Approach to Enhance University Students' Visualization of Molecular Geometry in Chemical Compounds: A Case Study in Saudi Arabia. *Journal of Radiation Research and Applied Sciences*, 18(1). <https://doi.org/10.1016/J.Jrras.2024.101283>
- Ardianti, S., Wiji, W., & Widhiyanti, T. (2021). Conceptions And Troublesome Knowledge on Acid-Base Using the Two-Tier Multiple-Choice Diagnostic Test. *Journal of Physics: Conference Series*, 2098(1). <https://doi.org/10.1088/1742-6596/2098/1/012032>
- Azwar, S. (2012). *Penyusunan Skala Psikologi (Edisi 2)*. Pustaka Pelajar.
- Crandell, O. M., & Pazicni, S. (2022). Leveraging Cognitive Resources to Investigate the Impact of Molecular Orientation on Students' Activation of Symmetry Resources. *Chemistry Education Research and Practice*, 24(1), 353–368. <https://doi.org/10.1039/D2rp00164k>
- Crandell, O. M., & Pazicni, S. (2024). Characterizing Students' Identification of Reflection Planes in Inorganic Chemistry Symmetry Tasks. *Journal Of Chemical Education*, 101(11). <https://doi.org/10.1021/Acs.Jchemed.4c00792>
- Creswell, J. W. (2012). *Educational Research: Planning, Conducting, And Evaluating Quantitative and Qualitative Research (4th Ed)* (4th Ed.). Pearson Education.
- Erlina, W., D. P., C., C., H., N., U., M., & Wafiq, A. F. (2024). Reconstructing Perspectives: Investigating How Molecular Geometry Cards (Mgcards) And Molecular Model Building (MMB) Disrupt Students' Alternative Notions of Molecular Structure - A Qualitative Study. *Chemistry Education Research and Practice*, 25(4), 1052–1070. <https://doi.org/10.1039/D3rp00038a>
- Fombona-Pascual, A., Fombona, J., & Vicente, R. (2022). Augmented Reality: A Review of a Way to Represent and Manipulate 3D Chemical Structures. *Journal of Chemical Information and Modeling*, 62(8), 1863–1872. <https://doi.org/10.1021/Acs.Jcim.1c01255>
- Habiddin, H., Farizka, L., & Shuid, A. N. Bin. (2023). Chemistry Students' Understanding of Lewis Structure, VSEPR Theory, Molecular Geometry, And Symmetry: A Cross-Sectional Study. *JTK (Jurnal Tadris Kimiya)*, 8(1), 1–9. <https://doi.org/10.15575/Jtk.V8i1.24410>
- Hasanah, D., Wiji, W., Mulyani, S., & Widhiyanti, T. (2023). Students' Mental Model Profiles on Chemical Bonding Concept Using a Two-Tier Mental Model Diagnostic Test (TDM-Two-Tier). *Jurnal Penelitian Pendidikan IPA*, 9(11), 10466–10474. <https://doi.org/10.29303/Jppipa.V9i11.3811>
- Kapici, H. O. (2023). From Symbolic Representation to Submicroscopic One: Preservice Science Teachers' Struggle with Chemical Representation Levels in Chemistry. *International Journal of Research in Education and Science*, 9(1), 134–147. <https://doi.org/10.46328/Ijres.3122>
- Kiernan, N. A., Manches, A., & Seery, M. K. (2021). The Role of Visuospatial Thinking in Students' Predictions of Molecular Geometry. *Chemistry Education Research and Practice*, 22(3). <https://doi.org/10.1039/D0rp00354a>
- Kiernan, N. A., Manches, A., & Seery, M. K. (2024). Resources For Reasoning of Chemistry Concepts: Multimodal Molecular Geometry. *Chemistry Education Research and Practice*, 25(2). <https://doi.org/10.1039/D3rp00186e>
- Kuit, V. K., & Osman, K. (2021). Chembond3d E-Module Effectiveness in Enhancing Students' Knowledge of Chemical Bonding Concept and Visual-Spatial Skills. *European Journal of Science and Mathematics Education*, 9(4), 252–264. <https://doi.org/10.30935/SCIMATH/11263>
- Langitasari, I., & Robandi, B. (2023). Analysis of the Student's Ability to Interconnect Macro-Submicro-Symbolic Representation on Electrolyte Solution Concept. *Educhemia (Jurnal Kimia Dan Pendidikan)*, 8(1), 84–96. <https://doi.org/10.30870/Educhemia.V8i1.19974>
- Mardiyyaningsih, A. N., Erlina, E., Ulfah, M., & Wafiq, A. F. (2023). Validity And Reliability of the Two-Tier Diagnostic Test to Identify Students' Alternative Conceptions of Intermolecular Forces. *Jurnal Penelitian Pendidikan IPA*, 9(6), 4375–4381. <https://doi.org/10.29303/Jppipa.V9i6.2797>
- Permana, I., Nuraeni, E., Pursitasari, I. D., & Yulianti, Y. (2023). Application of Augmented Reality Module For Alkane Derivatives to Improve Students' Spatial Ability And Mastery of Concepts. *Jurnal Pendidikan Sains Indonesia*, 11(4), 784–793. <https://doi.org/10.24815/Jpsi.V11i4.31854>

- Phajan, T., Cojorn, K., & Dien, T. N. N. (2025). Exploring The Representational Competence of Eleventh-Grade Students on the Rates of Chemical Reactions. *Jurnal Pendidikan IPA Indonesia*, 14(2), 351–363. <https://doi.org/10.15294/jpii.v14i2.24509>
- Pratamadita, A., & Dwiningsih, K. (2022). Development Of Interactive E-Modules as a Learning Media to Train Visual-Spatial Intelligence on Intermolecular Force Materials. *Jurnal Kependidikan: Jurnal Hasil Penelitian Dan Kajian Kepustakaan Di Bidang Pendidikan, Pengajaran, Dan Pembelajaran*, 8(1). <https://doi.org/10.33394/jk.v8i1.4521>
- Rahmawati, Y., Dianhar, H., & Arifin, F. (2021). Analyzing Students' Spatial Abilities in Chemistry Learning Using 3d Virtual Representation. *Education Sciences*, 11(4), 1–22. <https://doi.org/10.3390/educsci11040185>
- Ramadhan, M. F., Heliawati, L., & Rubini, B. (2025). The Role of Spatial Ability in High School Students' Understanding of Molecular Geometry. *Journal of Environment and Sustainability Education*, 3(1), 99–107. <https://doi.org/10.62672/joease.v3i1.56>
- Rohmah, N. U., & Hidayah, F. F. (2022). The Effectiveness of Using 3D Simulation Media in Online Learning of Molecular Geometry on Improving Learning. *Journal of Chemistry Education Research*, 6(1), 19–25.
- Salame, I. I., & Kabir, S. A. (2022). Examining Students' Spatial Ability and Its Impact on The Learning of Stereochemistry. *Interdisciplinary Journal of Environmental and Science Education*, 18(4), 1–9. <https://doi.org/10.21601/ijese/12099>
- Saputra, D. H., & Dwiningsih, K. (2025). Integration Of A 3D Animation Flipbook to Enhance Spatial Visualization in Molecular Geometry Learning. *Indonesian Journal of Educational Development (IJED)*, 6(3), 798–815. <https://doi.org/10.59672/ijed.v6i3.5401>
- Stewart, E. E. M., Hartmann, F. T., Morgenstern, Y., Storrs, K. R., Maiello, G., & Fleming, R. W. (2022). Mental Object Rotation Based on Two-Dimensional Visual Representations. *Current Biology*, 32(21), R1224–R1225. <https://doi.org/10.1016/j.cub.2022.09.036>
- Stiawan, E., Basuki, R., Liliasari, L., & Rohman, I. (2022). Enhancement Of Indonesian High School Student Conceptual Mastery on VESPR Topic Using Virtual Simulation of Molecule Shapes: A Case Study of Quasi-Experimental Evidence. *Jurnal Pendidikan IPA Indonesia*, 11(4), 511–518. <https://doi.org/10.15294/jpii.v11i4.36385>
- Talanquer, V. (2022). The Complexity of Reasoning About and With Chemical Representations. *JACS Au*, 2(12), 2658–2669. <https://doi.org/10.1021/jacsau.2c00498>
- Thayban, T., Munandar, H., Kurniawati, E., Alio, L., & Naqib Bin Shuid, A. (2022). Spatial Ability: Measuring Its Contribution to Symmetry Understanding. Dalam *Jurnal Pembelajaran Kimia OJS* (Vol. 7, No. 2).
- Treagust, D. F. (1988). Development And Use of Diagnostic Tests to Evaluate Students' Misconceptions in Science. *International Journal of Science Education*, 10(2), 159–169. <https://doi.org/10.1080/0950069880100204>
- Vanzal, T., & Dwiningsih, K. (2023). Effectiveness Of Android-Based Mobile Learning (M-Learning) on Molecular Shape Sub-Materials to Improve Students' Visual-Spatial Intelligence. *Jurnal Penelitian Pendidikan IPA*, 9(9), 7474–7483. <https://doi.org/10.29303/jppipa.v9i9.4738>
- Winata, A. (2023). Enhancing Students' Visual-Spatial Abilities Through the Use of Bonat Berakal Media in Understanding Shapes of Molecules. *Hydrogen: Jurnal Kependidikan Kimia*, 11(1), 40. <https://doi.org/10.33394/hjkk.v11i1.6911>
- Yamtinah, S., Shidiq, A. S., Pamungkas, Y. P., Sudarmin, S., & Ramadhani, D. G. (2026). Mapping Spatial Reasoning Profiles Using Two-Tier VR-Assisted Questions: A Cognitive Visualization Approach. *Chemistry Teacher International*, 1–18. <https://doi.org/10.1515/Cti-2025-0051>