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INQUIRY-BASED LEARNING IN STEREOCHEMISTRY: STRENGTHENING 3D VISUALIZATION AND CONCEPTUAL UNDERSTANDING

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This study examined the impact of cooperative inquiry-based learning (IBL) using hands-on molecular models on the learning of organic stereochemistry in a high school setting. In this approach, teacher support is minimal, allowing students to independently construct new concepts while reviewing previously acquired knowledge. The research was conducted with two parallel groups: an experimental group, which participated in the IBL interactive activities, and a control group, which followed a traditional instructional approach. The experimental group engaged in a three-phase learning cycle of exploration, concept formation, and application. Activities were conducted through cooperative small-group work, encouraging students to discuss ideas and compare molecular structures. Students constructed and analyzed 3D models of organic stereoisomers, applying their observations to formulate rules for different types of stereoisomerism and to visualize molecular structures more effectively. After completing the activities, students completed a questionnaire regarding their attitudes and experiences, as well as a knowledge test. The questionnaire revealed that students found the activities motivating, useful, and accessible, highlighting increased engagement, improved conceptual understanding, and a preference for interactive model-based approaches over traditional lectures. Both groups completed a knowledge test, and the results showed that the experimental group scored significantly higher. Statistical analysis confirmed that these differences were statistically significant. These findings indicate that cooperative IBL using hands-on molecular models is an effective teaching strategy for improving conceptual understanding, mastery of stereochemical concepts, and the development of higher-order thinking. Moreover, students demonstrated an enhanced ability to apply learned concepts and terminology in new and more complex contexts, indicating a deeper and more lasting understanding of the material.

Keywords: stereochemistry; three-dimensional visualization; inquiry-based learning; cooperative learning; conceptual understanding

УЧЕЊЕ БАЗИРАНО НА ИСТРАЖУВАЊЕ ВО СТЕРЕОХЕМИЈАТА: ПОДОБРУВАЊЕ НА 3Д-ВИЗУАЛИЗАЦИЈАТА И КОНЦЕПТУАЛНОТО РАЗБИРАЊЕ

Во ова истражување е испитувано влијанието на кооперативното учење базирано на истражување (IBL) со примена на практична работа со молекуларни модели, врз учењето на органската стереохемија во средношколски услови. При овој пристап поддршката од наставникот е минимална, овозможувајќи им на учениците самостојно да конструираат нови концепти, истовремено повторувајќи ги претходно стекнатите знаења. Истражувањето беше спроведено со две паралелни групи: експериментална група, која учествуваше во интерактивностите базирани на IBL, и контролна група, која следеше традиционален наставен пристап. Експерименталната група беше вклучена во трифазен циклус на учење: истражување, формирање на концепти и примена. Активностите се реализираа преку кооперативна работа во мали групи, поттикнувајќи ги учениците да дискутираат и да споредуваат молекуларни структури. Учениците конструираа и анализираа тридимензионални модели на органски стереоизомери, применувајќи ги своите набљудувања за формулирање правила за различни типови стереоизомерија и за поефикасна визуализација на молекуларните структури. По завршувањето на активностите, учениците пополнија прашалник за нивните ставови и искуства, како и тест за проверка на знаењето. Резултатите од прашалникот покажаа дека учениците ги оцениле активностите како мотивирачки, корисни и достапни, истакнувајќи зголемена ангажираност, подобро концептуално разбирање и преферирање интерактивни пристапи базирани на модели во однос на традиционалните предавања. Двете групи решаваа тест на знаење, при што резултатите покажаа дека експерименталната група постигнала значително повисоки резултати. Статистичката анализа потврди дека овие разлики се статистички значајни. Овие наоди укажуваат дека кооперативното учење базирано на истражување со примена на практична работа со молекуларни модели, претставува ефективна наставна стратегија за подобрување на концептуалното разбирање, совладување на стереохемиските концепти и развој на повисоки когнитивни вештини. Дополнително, учениците покажаа зголемена способност за примена на научените концепти и терминологија во нови и покомплексни контексти, што укажува на подлабоко и потрајно разбирање на материјалот.

Клучни зборови: стереохемија; тридимензионална визуализација;
учење базирано на истражување; кооперативно учење; концептуално разбирање

1. INTRODUCTION

One of the most important and challenging areas of organic chemistry is stereochemistry, which deals with the three-dimensional arrangement of atoms in molecules and the effect that this spatial configuration has on their physicochemical properties, reactivity, and biological activity.[1–3] Beyond its importance for biomolecules in living organisms, stereochemistry also holds particular significance in pharmaceutical sciences.

Due to the great fundamental and practical importance of stereochemistry, it is essential to introduce its principles beginning in secondary education. However, stereochemistry is often considered difficult because it requires students to mentally visualize three-dimensional molecules and to represent them symbolically in two dimensions by drawing their corresponding structures. Many studies have confirmed that students struggle to convert 2D formulas into 3D structures and *vice versa*,[4–8] especially when multiple chiral centers are involved. In this respect, one of the greatest challenges is the abstract nature of this visualization. As a result, students face difficulties with more complex concepts, such as the stereochemical configuration and conformation of organic molecules,[9,10] which often lead to misconceptions and difficulties in applying theoretical knowledge in practical contexts.

Given the problems that students face when studying organic stereochemistry, educational research in this area has significantly increased over the last two decades. Foundational studies showed that students often misconstrue isomerism as merely compounds with identical functional groups.[11–13] Building on these findings, more recent work has explored innovative methods for teaching isomerism[14] and strategies ranging from stereochemical configuration tasks to 3D visualization tools,[15–19] programming and web-based tutorials,[20–22] augmented reality applications,[23] and even game-based learning.[24–26] Recent studies highlight the application of diverse teaching models in stereochemistry education.[27–30]

According to the broader chemistry education frameworks proposed by Johnstone[31] and Talanquer,[32] developing conceptual understanding in chemistry requires coordination between macroscopic, submicroscopic, and symbolic levels of representation. This framework is particularly relevant in stereochemistry, where students must connect symbolic molecular drawings with three-dimensional spatial structures. The progressive introduction of new stereochemical concepts, progressing from macroscopic observation to molecular explanation and symbolic representation, is consistent with the constructivist approach,[33] a student-centered framework emphasizing incremental learning.

One of the teaching strategies within the constructivist framework is inquiry-based learning (IBL). In this approach, students take an active role; rather than passively receiving information, they formulate hypotheses, test ideas, and engage in activities that promote problem-solving abilities, reasoning, and critical thinking.[34–36] Studies demonstrate that IBL in STEM (science, technology, engineering, and mathematics) education fosters deeper conceptual understanding.[37–38]

The application of IBL with concrete 3D molecular models, both physical and virtual, in stereochemistry instruction significantly improves students' understanding of the three-dimensional structures of organic molecules and clarifies complex concepts such as constitutional isomerism, chirality, stereoisomerism, and conformational analysis.[29,35,39] Beyond content mastery, model-based learning cultivates broader skills such as spatial reasoning, visualization, and evidence-based thinking that facilitate further study in chemistry and related sciences.[35,39] Buchner and Kerres[41] demonstrated that integrating virtual technologies into IBL enhances student motivation when tackling stereochemical problems involving chirality. Moreover, a pilot study revealed that virtual models significantly improve accuracy in distinguishing between enantiomers and diastereomers.[42]

An essential component of inquiry-based learning is cooperative learning. This strategy encourages active student participation through small-group work.[43] In stereochemistry, such activities facilitate the discussion and exchange of ideas, enable students to explain concepts to one another, and foster collaborative problem-solving. Through cooperative learning, students deepen their understanding, evaluate diverse perspectives from peers, and strengthen their critical thinking and spatial reasoning skills. Consequently, the approach aids in visualizing three-dimensional molecular structures and mastering abstract concepts such as chirality and stereoisomerism.[44]

Despite these advantages, traditional methods (2D diagrams, blackboard sketches, and lecture-based teaching) remain common in Macedonian high schools. However, these approaches often fail to effectively convey the three-dimensional structure of molecules. In such traditional settings, the teacher typically presents molecular models for observation, while students rarely manipulate, explore, or test ideas with the models. This lack of interaction limits opportunities for active inquiry and deeper conceptual understanding.

To address these challenges within Macedonian high-school education regarding stereochemistry, we have developed a series of inquiry-based learning (IBL) activities organized into a three-phase learning cycle: exploration, concept invention, and application.[45] In the first phase, students investigate the structural features of a given pair of stereoisomers. In the second phase, concept invention, they formulate a definition of the specific type of isomerism based on their observations. The aim of the final application phase is for students to apply the working definition to a new pair of stereoisomers that incorporates additional features, thereby refining and extending the original definition. In this paper, we present the results of implementing this IBL learning cycle to assess students' conceptual understanding of stereochemistry. To further clarify the aims of the study, the following research questions were formulated:

1. Does inquiry-based learning using hands-on molecular models improve students’ understanding of stereochemical concepts?
2. Does the use of cooperative model-based activities enhance students’ three-dimensional visualization abilities?
3. How do students perceive the effectiveness and usefulness of inquiry-based stereochemistry activities?

2. METHODS

This study employed a quasi-experimental research design to examine the effects of inquiry-based learning (IBL) using hands-on molecular models on students’ understanding of stereochemistry. The study involved an experimental group, which participated in cooperative inquiry-based activities, and a control group, which received traditional instruction. Data were collected through a questionnaire assessing students’ perceptions and a knowledge test evaluating conceptual understanding and spatial visualization skills.

2.1. *Learning environment*

Students were assigned to small groups of three to four members to encourage cooperation and active participation. This group size was deliberately chosen: it was large enough to foster discussion and the meaningful exchange of ideas, while remaining small enough to ensure that each student had the opportunity to contribute. This collaborative arrangement aligns with the principles of inquiry-based learning (IBL), in which cooperative problem-solving and peer explanation are key for developing a deeper understanding.

Each group was provided with a worksheet (Supplementary information 1) that guided them step-by-step through the activity, along with a molecular model kit (Fig. 1). The use of these models provided students with hands-on experience of molecular geometry and helped them move beyond abstract representations to concert engagement with the three-dimensional architecture of molecules.

The activity was conducted in a standard classroom arranged to support group work. Tables and chairs were arranged in three rows, with each row accommodating two to three groups. This setup enabled students to face one another while maintaining a clear view of both the teacher and the whiteboard. The whiteboard served as a central point for explanations and demonstrations, ensuring that instructions were readily accessible and that students' questions could be addressed as they progressed through the activity.

Fig. 1. Contents of a molecular model kit. Each group of students received one model kit (Pearson Molecular Model Set, Prentice Hall, https://www.amazon.com/Prentice-Molecular-Model-Organic-Chemistry/dp/0205081363)

2.2. *Participants*

A total of 134 third-year students from two high schools in Skopje, North Macedonia, SUGS (Secondary Schools of the City of Skopje) “Nikola Karev” and SUGS “Rade Jovchevski-Korchagin”, participated in the study. The sample included 70 students in the experimental group and 64 students in the control group. The students were approximately 16–17 years old, with 64.9 % female and 35.1 % male participants. The activity was implemented during regular chemistry lessons, thereby providing a natural context for observing how students responded to this alternative teaching approach

At both schools, two intact classes participated in the study. Within each school, one class was randomly assigned to the experimental group and the other to the control group. Notably, the same teacher had instructed both groups at each school prior to the intervention, thereby reducing potential teacher-related variability and enhancing group comparability. Additionally, the experimental and control groups demonstrated similar baseline achievement in chemistry, further ensuring comparability ahead of the intervention.

Following the activity, students completed an online questionnaire (Supplementary Information 2) designed to assess their perceptions of the lesson. The questionnaire included both closed- and open-ended questions, enabling students both to rate specific aspects, such as clarity and usefulness, and to articulate their impressions in their own words. This dual approach to data collection yielded a more comprehensive overview of their experience.

Prior to the study, verbal consent was obtained from both the subject teachers and participating students. Participation was voluntary, and all questionnaire responses and test results were collected anonymously to protect student privacy and ensure compliance with the ethical principles of educational research. The study received approval from the relevant institutions, and all participants provided informed consent.

2.3. *Research design*

Hands-on molecular modeling activities were integrated into the chemistry classroom to enhance students' understanding of stereochemistry and foster the development of research skills. The activity was carefully designed and implemented across three sessions, each featuring a distinct aim and methodological approach. Prior to the activity, students were expected to know carbon valence, the interconversion of structural and skeletal formulas, and three-dimensional molecular representation using solid and dashed wedge bonds. Equipped with this foundational knowledge, students were ready to construct, analyze, and compare 3D molecular models, thereby applying conceptual knowledge to practical tasks while developing spatial reasoning, critical thinking, and an inquiry-based mindset. Through this structured activity, students gained confidence in applying abstract stereochemical concepts to concrete molecular structures, reinforcing the link between theory and practice.

2.4. *Activity procedure*

2.4.1. *Session 1 part 1 – Constitutional isomers*

During the first phase of the activity, students constructed 3D models of three isomeric compounds: **A** (*cis*-1-bromo-2-methylcyclobutane), **B** (*cis*-1-bromo-3-methylcyclobutane), and **C** (*trans*-1-bromo-2-methylcyclobutane) (Fig. 2). To simplify the models and facilitate visualization, hydrogen atoms were intentionally omitted.

Exploration. Students independently analyzed the 3D models of isomers **A** and **B**. Without direct guidance from the teacher, they compared the structures and identified key features:

- Both structures share the same molecular formula;
- **A** and **B** are disubstituted cyclobutane compounds with bromine and a methyl group;
- In structure **B**, the substituents are separated by a –CH_2– group, whereas in structure **A** they are adjacent.

Concept invention. After recognizing these differences, students were informed that structures **A** and **B** are skeletal isomers. To promote conceptual understanding rather than memorization, they were asked to formulate a definition independently. The definition they proposed was: "Two compounds that have the same molecular formula but a different connectivity of atoms."

Application. Students then applied this definition to propose a new constitutional isomer of compound **A**, distinct from structure **B**. If their proposed structure corresponded to one of the provided models, they constructed two identical models to verify their equivalence and to correct any misconceptions. Figure 3 illustrates the constitutional isomers proposed by the students.

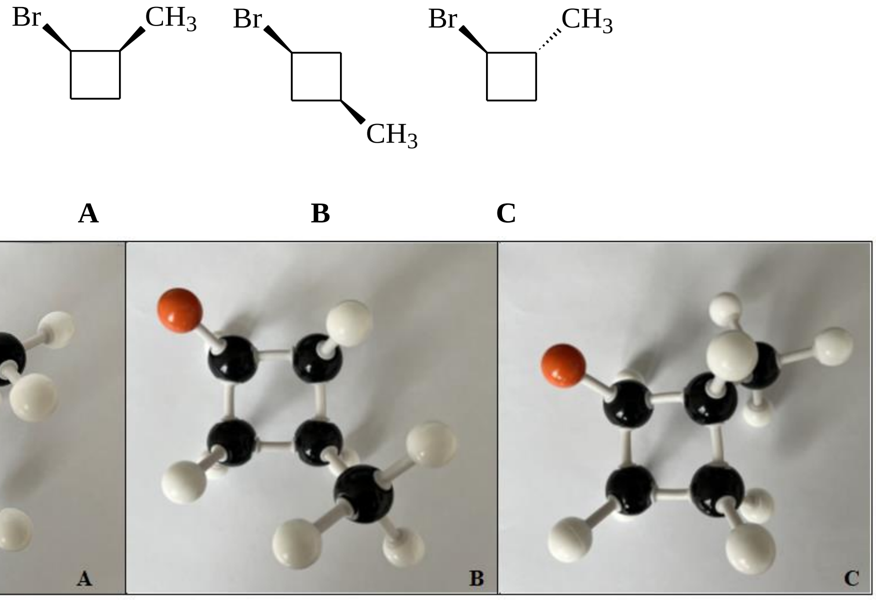

Fig. 2. Three isomeric compounds (A: *cis*-1-bromo-2-methylcyclobutane; B: *cis*-1-bromo-3-methylcyclobutane; C: *trans*-1-bromo-2-methylcyclobutane) and their concrete molecular models. Bromine atoms are represented by orange spheres

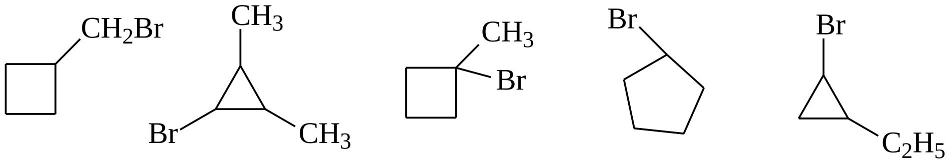

Fig. 3. Constitutional isomers of structure **A** proposed by the students

2.4.2. *Session 1 part 2 – Geometric isomers*

Exploration. During the second part of the first session, students analyzed the pre-constructed models of structures **A** and **C**. They observed that both structures possess the same molecular formula (C_5H_9Br) and the same atom connectivity, but exhibit differences in their spatial arrangement. This phase allowed students to independently identify these differences without direct guidance from the teacher.

Concept Invention. After recognizing that structures **A** and **C** differ only in their spatial orientation, the teacher introduced the concept of geometric (*cis/trans*) isomerism. Students were then encouraged to independently formulate a definition for geometric isomerism. The definition they proposed was: "Two compounds that have the same molecular formula and same atom connectivity, but different spatial arrangements."

The teacher additionally explained that geometric isomerism arises from restricted rotation around a carbon-carbon double bond or within a ring structure. For this type of isomerism to occur, each carbon atom involved in the double bond must be bonded to two different substituents, thereby allowing distinct spatial arrangements (*cis/trans*).

Application. With the definition clarified, students were asked to provide another example of geometric isomers based on the molecular formula ($C_2H_2Br_2$). This activity reinforced their understanding and demonstrated the applicability of the definition developed in the exploration phase. Figure 4 depicts the geometric isomers constructed by one of the groups during this activity.

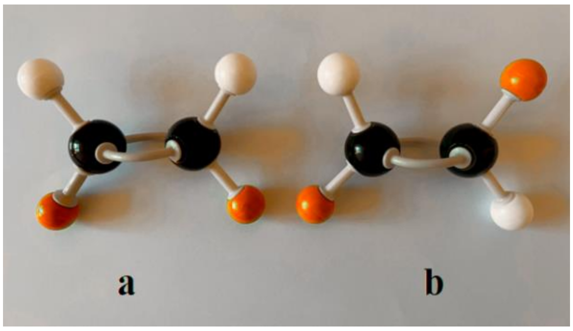

Fig. 4. *Cis* (a) and *trans* (b) geometric isomers of 1,2-dibromoethene, as constructed by students. Hydrogen atoms are represented by white spheres, and bromine atoms are represented by orange spheres

2.4.3. *Session 2 – Stereoisomers with chiral (stereogenic) centers*

Exploration. At the outset of the second session, students were tasked with constructing 3D molecular models of two compounds, labeled **A** and **B**. After building the models, they compared the models by attempting to superimpose one onto the other. They observed that, although sharing the same molecular formula and identical atom connectivity, the compounds could not be superimposed and exhibited a relationship analogous to that of an object and its mirror image. The enantiomers **A** and **B**, shown in Figure 5, were constructed by the students during this activity.

Concept invention. At this stage, the teacher explained that compounds **A** and **B** are enantiomers (chiral molecules) and asked students to independently formulate a definition of optical isomerism based on their observations. The students proposed: "Two compounds that have the same molecular formula and atom connectivity, but have different spatial arrangements and are not superimposable, with the mirror image of each other."

The teacher subsequently introduced the concepts of chirality and chiral centers, explaining that chirality is the property of molecules that renders them non-superimposable on their mirror images. A chiral center is typically an sp^3-hybridized carbon atom bonded to four different substituents, and its presence gives rise to optical isomerism. The teacher further demonstrated how chiral centers are designated and emphasized that molecules may contain multiple chiral centers, leading to compounds with distinct physical and chemical properties. This discussion provided students with a comprehensive understanding of the significance of chirality and chiral centers, especially in biochemistry.

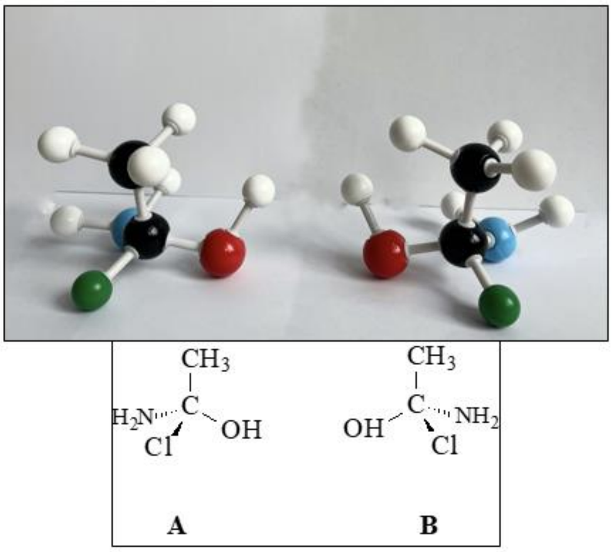

Fig. 5. Optical isomers A ((1*R*)-1-amino-1-chloroethan-1-ol) and B ((1*S*)-1-amino-1-chloroethan-1-ol), along with their molecular models. In the models, the hydroxyl group is represented by a red sphere bonded to a white sphere, chlorine by a green sphere, and the amino group by a blue sphere bonded to two white spheres

Application. In the final phase, students were tasked with proposing an enantiomer of a compound with the molecular formula $C_3H_5BrO_2$, ensuring the compound contained a carboxyl group (–COOH). This exercise allowed students to apply the previously formulated definition of optical isomerism to a new case and demonstrate their ability to identify the conditions required for the existence of a chiral molecule. Figure 6 shows the structures and molecular models proposed by students.

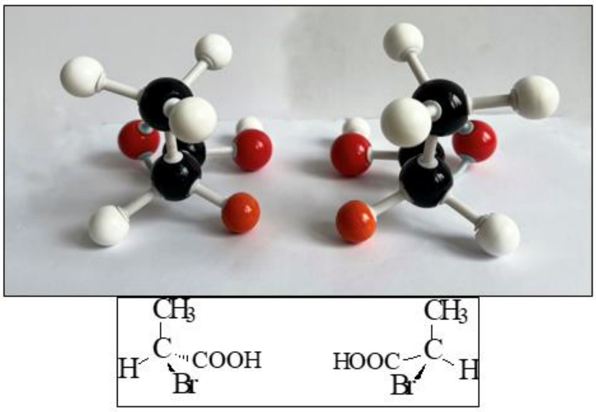

Fig. 6. Student-proposed structures and molecular models of enantiomers of $C_3H_5BrO_2$ containing a carboxyl group (–COOH)

2.4.4. *Session 3 – Conformational isomers (conformers)*

Exploration. In the final session, students were tasked with constructing a 3D model of ethane (CH_3–CH_3). By visualizing the molecule, they became familiar with the concept of the Newman projection, which depicts the spatial arrangement of atoms around the carbon–carbon (C–C) bond and facilitates the comparison of different conformations in aliphatic alkanes. Subsequently, students identified and sketched the two basic conformations of ethane, eclipsed and staggered, by carefully examining their constructed models. In Figure 7, the students' models alongside their corresponding graphical representations.

Concept invention. When analyzing the two conformations, students concluded that the staggered conformation is energetically more stable because the atoms are maximally separated, thereby minimizing torsional and steric interactions. In contrast, the eclipsed conformation is less stable due to increased energetic strain resulting from closer atomic proximity. This observation allowed students to understand how the three-dimensional structure of a molecule influences its stability.

Application. In the final phase, students constructed a 3D model of butane and analyzed the atomic arrangement around the C2–C3 bond. Using their understanding of ethane, they identified the staggered and eclipsed conformations of butane. By rotating the C2–C3 bond, they observed that one eclipsed conformation exhibited greater strain (less energetically stable) than the other, analogous to the differences observed between the two staggered conformations. The teacher subsequently introduced the concept of steric strain and explained its impact on stability. This exercise enabled students to connect previously learned concepts to more complex alkanes, thereby developing a deeper understanding of conformational isomerism and the effects of steric interactions on molecular stability, while also recognizing its dynamic nature.

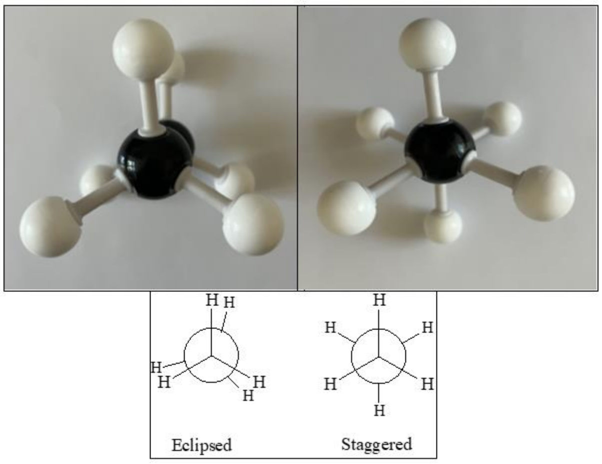

Fig. 7. Students' molecular models of ethane conformations and their corresponding graphical representations (eclipsed on the left and staggered on the right).

Table 1 provides a structured overview of the learning process and activities across all three sessions, with each session's phases presented separately. This summary demonstrates how the activities supported the development of students' skills in hands-on molecular modeling, understanding different types of isomers, and the application of theoretical knowledge to practical tasks.

2.5 *Research instruments*

The questionnaire consisted of ten Likert-type items designed to assess students’ perceptions of engagement, motivation, conceptual understanding, and usefulness of the implemented activities. Responses were recorded on a five-point Likert scale ranging from strongly disagree to strongly agree. The instrument was adapted from previously published questionnaires and demonstrated high internal consistency (Cronbach’s $\alpha = 0.87$).[46,47]

The knowledge test consisted of ten questions covering different stereochemical concepts, including molecular formulas, geometric isomerism, chirality, conformational analysis, and skeletal structure representation. Each correct answer was awarded one point, with a maximum possible score of 10 points. The test was designed in accordance with the intended learning outcomes of the implemented activities and reviewed by chemistry educators to ensure content validity. Students were given 45 minutes to complete the test.

Statistical analyses were conducted using JASP (Version 0.19.1) and Microsoft Excel.

Table 1

Summary of the main learning activities from all three sessions

Session	Part	Exploration	Concept invention	Application
1	Constitutional isomers	Students constructed models for isomers A, B, and C (with hydrogen atoms omitted). They independently analyzed the models of A and B.	A and B are constitutional isomers, defined as: "Two compounds that have the same molecular formula but a different connectivity of atoms."	Students proposed an additional constitutional isomer of A and constructed models to verify its correctness.
	Geometric isomers	Students analyzed models of A and C (the same formula and atom connectivity but different spatial arrangement)	Geometric isomers, defined as: "Two compounds that have the same molecular formula and same atom connectivity but different spatial arrangements."	Students provided another example of geometric isomers ($C_2H_2Br_2$)
2	Isomers with chiral centers	Students constructed 3D models of A and B and observed that they are non-superimposable mirror images.	Optical isomers, defined as: "Two compounds that have the same molecular formula and atom connectivity, but have different spatial arrangements and are not superimposable with the mirror image of each other." Teacher introduced chirality and chiral centers.	Students proposed an optical isomer with the molecular formula $C_3H_4O_2Br$ containing a – COOH group.
3	Conformational isomers	Students constructed 3D models of ethane, visualized Newman projections, and identified eclipsed and staggered conformations.	Staggered conformation is more stable and eclipsed is less stable. Students understand the influence of 3D structure on stability and steric interactions.	Students built models of butane, identified its eclipsed and staggered conformations, and analyzed the effects of steric strain stability, through conformational analysis

3. RESULTS AND DISCUSSIONS

3.1. *Questionnaire*

The questionnaire was administered following the three activity sessions to collect feedback on students' perceptions of and experiences with using molecular models. The results of the questionnaire are summarized in Table 2. All 77 students present during the classes completed the questionnaire electronically via the Google Forms platform.

Overall, students showed a high level of agreement (agree: 54 %; strongly agree: 39 %, across all ten statements) that applied activities, integrating molecular models into chemistry lessons and carried out through collaborative group work, enhanced their understanding of abstract concepts (Table 2, Statements 2 and 7).

These findings align with existing research showing that model-based learning enhances students' understanding of complex stereochemical concepts.[5,29,30] Moreover, the use of 3D molecular models further supports comprehension of 3D molecular structures,[17,23,40,48] and helps bridge the gap between two-dimensional and three-dimensional molecular representations.[4–16] Additionally, previous studies suggest that engaging students in cooperative, inquiry-based tasks promotes peer interaction and collaborative knowledge construction, thereby fostering deeper comprehension of the concepts covered in the activities.[37–43]

The activities were rated as highly engaging and motivating, with students actively participating in inquiry-based group tasks, which enhanced interaction and sustained attention throughout the lessons (Table 2, Statements 1, 3, and 4). This observation aligns with previous studies showing that interactive and hands-on teaching methods increase student engagement and motivation in learning stereochemistry,[21,24,30] while also leading to deeper conceptual understanding and enabling longer-term retention of acquired knowledge.[45]

Furthermore, the majority of students expressed a preference for this interactive and cooperative approach over traditional lecture-based teaching and emphasized the need for more frequent implementation of such activities in the chemistry curriculum in high schools in the Republic of Macedonia (Table 2, Statements 5 and 6). These results are corroborated by other studies,[29,39,42] which highlight a preference for active model-based learning over traditional lectures and demonstrate that combining physical and virtual tools enhances both motivation and conceptual understanding.[23,41]

Statement 8 reveals that students regarded molecular models to be a highly useful and effective tool for visualizing the three-dimensional structure of organic molecules and for understanding complex stereochemical concepts. They also found the models to be user-friendly and accessible, although 14.3 % remained neutral (Table 2, Statement 9). The implemented activity was evaluated as a meaningful and effective tool to support students' learning (Table 2, Statement 10), confirming that repeated hands-on engagement in small cooperative groups enhances students' confidence and sense of competence.[17,40] Moreover, the integration of tactile and visual exercises within these groups helped students overcome challenges in spatial visualization and fostered active discussion, collaborative reasoning, and joint problem-solving.[6,8]

In addition to the Likert-type statements, the questionnaire incorporated two open-ended questions designed to elicit students' perceptions of the most beneficial aspects of the activity and potential areas for improvement. This qualitative feedback provided a more complete picture of the activity's success. Of the 77 respondents, 46 provided specific comments in response to these questions.

The most frequently mentioned suggestion was for greater availability of molecular models. Many students expressed interest in using these models, or Lego bricks, more frequently during chemistry classes to support hands-on construction, visualization, and active participation.

Another prominent suggestion involved enhancing group interaction and increasing the frequency of interactive sessions. Students emphasized that the activities were motivating and encouraged collaborative learning. Some students suggested rotating the groups after each session or introducing competitive elements, which they believed would enhance greater dynamism and motivation. These findings align with those reported by other researchers.[25,26]

Several students expressed satisfaction with the overall design and organization of the activity, stating that no improvement was necessary. Others, however, suggested dividing the tasks into multiple sub-sessions or providing more time for completion, as they believed this would allow for better mastery of the material. Based on these results, it can be concluded that students found the activity highly engaging and useful for mastering the stereochemistry curriculum. Furthermore, they expressed strong interest in the greater inclusion of such practical and interactive approaches into chemistry teaching.[34,36]

Table 2

Results of the questionnaire regarding stereochemical sessions

Statement	**Strongly agree (%)**	**Agree (%)**	**Neutral (%)**	**Disagree (%)**	**Strongly disagree (%)**
1. This activity was interesting.	50.7	47.2	2.1	0	0
2. The activity can help me understand the concepts.	58.4	36.4	5.2	0	0
3. This activity motivates me to learn chemistry.	36.4	33.8	29.8	0	0
4. The activity encourages my participation in class.	37.6	54.2	8.2	0	0
5. I prefer this type of learning activity to traditional didactic lectures.	70.1	29.9	0	0	0
6. There should be more similar learning activities in the high school chemistry curriculum.	62.3	33.8	3.9	0	0
7. This type of lesson can help me understand the concepts studied.	66.2	33.8	0	0	0
8. Molecular models can help us visualize the three-dimensional nature of organic molecules.	63.6	36.4	0	0	0
9. The models are easy to use.	50.6	35.1	14.3	0	0
10. I think this is an important learning activity.	42.9	43.8	13.3	0	0

3.2. *Test analysis*

Seven students from the experimental group were absent during the knowledge testing session; therefore, the final statistical analysis included 70 students in the experimental group and 64 students in the control group.

The test was designed to evaluate a comprehensive range of stereochemical topics, integrating conceptual understanding and practical visualization skills, while providing insights into the effect of molecular model-based activities compared to traditional teaching (Supplementary Information 3). For comparison, the same assessment was administrated to a control group of 64 students who had studied identical stereochemical content using conventional teaching methods. Previous studies suggest that traditional teaching methods frequently fail to support students' comprehension of stereochemical concepts,[7,8,12] thereby underscoring the need for more interactive, visual, and collaborative learning strategies.[6] Pedagogical approaches that promote inquiry, peer interaction, discussion, and joint problem-solving have been shown to enhance conceptual understanding across various chemistry topics.[37,43]

The assessment consisted of ten questions designed to assess students' competence in various aspects of stereochemistry, including identifying and drawing organic structures, distinguishing stereochemical properties, recognizing geometric isomers, and ordering conformational isomers by stability. The tasks were designed to assess conceptual understanding through the application and visualization of stereochemical concepts rather than simple factual recall. This assessment design reflects previous studies emphasizing the importance of assessing both conceptual understanding and spatial visualization abilities in stereochemistry education,[4,10] while providing opportunities for active, discussion-driven learning that promotes collective analysis and conceptual integration.[9]

Four of the assessment questions (Questions 1, 3, 5, and 10) evaluated students' ability to determine molecular formulas, identify chiral centers, and draw skeletal isomers. Questions 2 and 8 focused on recognizing and representing geometric isomers, while Questions 4, 7, and 9 assessed the understanding of the stability of conformational isomers. Question 6 tested the students' ability to distinguish compounds that are not skeletal isomers of a given molecular formula. This comprehensive assessment approach aligns with studies showing that a combination of conceptual and visualization tasks more effectively reveals students' strengths and misconceptions in stereochemistry,[9,10] while also encouraging analytical reasoning and integrative understanding.

The results suggest notably difference in the results between the experimental and control groups regarding their knowledge and understanding of the covered stereochemical concepts. This outcome is consistent with research indicating that cooperative learning structures promote deeper conceptual processing through peer interaction and shared reasoning.[43] Students in the experimental group, who participated in classes featuring activities based on IBL principles, achieved superior performance on all ten questions compared to students in the control group, who attended classes following traditional teaching methods.[23,48]

The percentage of correct answers from students in the experimental group ranged from 75.71 % to 92.86 %, with an average success rate of 83.57 %. These results show that most students achieved a high level of mastery of the intended material. The relatively narrow performance variation across the ten questions (0.26–0.43) suggests a generally stable level of performance across different stereochemical tasks. These results align with studies highlighting the effectiveness of hands-on and visual learning strategies in promoting accurate and consistent comprehension of stereochemical concepts.[6,7,17]

In contrast, the percentage of correct answers among students in the control group was significantly lower, ranging from 6.25 % to 84.38 %, with an average success rate of approximately 48.12 %. This result supports previous findings[8,12] that traditional teaching methods frequently result in inconsistent understanding and difficulties in visualizing three-dimensional molecular structures. In the present study, students in the control group showed the greatest difficulties with questions requiring such visualization (Questions 3 and 10), indicating a limited ability to grasp the three-dimensional characteristics of organic molecules. The somewhat broader variability observed in the control group (0.24–0.50) may reflect differences in students' understanding across various stereochemical tasks.

For enhanced clarity, Table 3 and Figure 8 present the percentage of correct answers, standard deviations, and standard errors for each question for the experimental and control groups, with corresponding error bars included in the figure.

Table 3

Percentages of correct answers per question with standard deviations (SD) and standard errors (SE), for experimental and control groups

Question	Experimental group			Control group		
	Corr. ans. (%)	*SD*	*SE*	Corr. ans. (%)	*SD*	*SE*
1	81.43	0.39	0.044	39.06	0.49	0.061
2	91.43	0.28	0.033	65.63	0.47	0.06
3	82.86	0.38	0.044	6.25	0.24	0.03
4	75.71	0.43	0.049	42.19	0.49	0.062
5	81.43	0.39	0.044	51.56	0.5	0.062
6	92.86	0.26	0.029	84.38	0.36	0.045
7	87.14	0.33	0.039	73.44	0.44	0.055
8	78.57	0.41	0.047	40.63	0.49	0.062
9	81.43	0.39	0.044	57.81	0.49	0.062
10	82.86	0.38	0.044	20.31	0.4	0.05

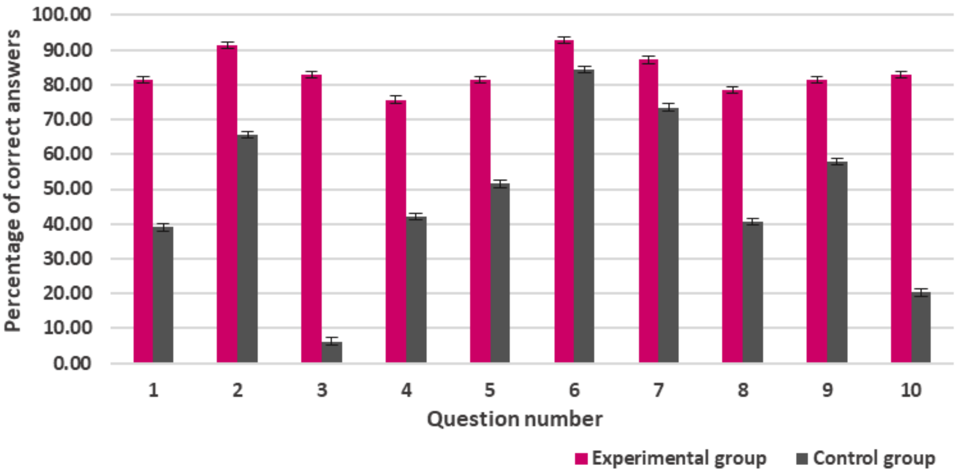

Fig. 8. Comparison of the results achieved from the experimental and control group

As shown in Figure 8, the experimental group, which completed the test after using the interactive molecular models, performed significantly better compared with the control group. The most notable differences emerged in questions requiring more complex spatial reasoning and active analysis of organic molecular structures.[17,23]

The most challenging questions for students in the control group were Questions 3 and 10, which required the application of chirality and stereoisomerism concepts. In Question 3, students struggled to draw the skeletal formula of a chiral aldehyde, reflecting limited three-dimensional visualization skills. Similarly, in Question 10, where students were tasked with constructing a skeletal isomer from a given molecular formula, they exhibited notable difficulties. These observations align with earlier findings that students often fail to translate two-dimensional molecular representations into three-dimensional structures without interactive or model-based learning aids.[4,10]

Conversely, students in the experimental group achieved much better results in identifying and drawing these structures, underscoring the value of interactive activities in developing conceptual and visual understanding of stereochemical concepts.[16,30]

Differences were also evident in questions on geometric isomers (Questions 2 and 8) and conformational isomers (Questions 4, 7, and 9), where the control group's answers showed considerable variability and inconsistency. Once again, the experimental group demonstrated stronger problem-solving skills and appropriate application of prior knowledge.[5,29,30]

Collectively, these findings show that implementing interactive and visual activities with molecular models in chemistry teaching, particularly those promoting active, student-centered, and collaborative learning, not only improves students' knowledge but also enhances motivation and engagement, thereby enabling more effective and comprehensive understanding of stereochemistry content. More frequent integration of such activities into the standard chemistry curriculum could significantly improve the learning outcomes for complex topics such as stereochemistry.[29,39,41,42]

To demonstrate that the obtained results were not attributable to chance but rather reflected the impact of the implemented activities within the experimental group, an independent samples Welch's *t*-test was conducted. The results of the analysis are presented in Table 4.

Table 4

Descriptive statistics and t-test outcomes for experimental vs. control group

Group	n	M/%	SD	ΔM/%	t	$t_{(crit.)(two\text{-}tail)}$	df	p
Experimental	70	83.57	10.83	35.45	14.28	1.98	106	< 0.001
Control	64	48.12	16.76					

Note: M – mean score (%); SD – standard deviation; ΔM^* – difference between means; t – t-test value; $t_{(crit)}$ – critical value; df – degrees of freedom; p – p-value.

An independent samples Welch's *t*-test revealed that the experimental group (M = 83.57, SD = 10.9, n = 70) scored significantly higher than the control group (M = 48.13, SD = 16.9, n = 64), $t(106)$ = 14.28, p < 0.001. Collectively, these results indicate that the observed differences are attributable to the implementation of the well-designed IBL activities.

Beyond statistical significance, the magnitude of the difference (ΔM = 35. 45 %) highlights the strong practical impact of the implemented IBL activities, suggesting that well-designed inquiry-based learning strategies can serve as a powerful tool for enhancing student engagement and performance in science education. These results further highlight the pedagogical potential of inquiry-based learning. Although the results demonstrated significant immediate learning gains, the study design did not include a delayed post-test. Future studies could incorporate follow-up assessments to determine whether the observed improvements persist over time. The integration of interactive, model-based activities into the chemistry curriculum fosters deeper conceptual understanding and develops students' spatial reasoning skills, thereby offering a valuable approach for science education. Future research should examine whether these effects persist across other students and educational levels.

Additionally, the study was conducted in only two high schools within the Republic of Macedonia, thereby limiting the generalizability of the findings. Consequently, the results may reflect contextual factors specific to these schools, such as curriculum implementation, teacher practices, and student demographics. Future research should replicate these activities across a wider range of schools and educational contexts to evaluate their generalizability and broader transferability.

4. CONCLUSIONS

Based on the findings of this investigation, several conclusions may be drawn. Statistical analysis showed that students in the experimental group achieved significantly higher results compared with the control group. These differences were particularly evident in tasks involving three-dimensional visualization of organic structures, identification of chiral centers, and drawing of skeletal isomers. The results indicate that collaborative learning applying IBL strategies and integrating interactive activities with hands-on molecular models exerts a significant positive effect on students, thereby enhancing their understanding of stereochemical content.

Analysis of the questionnaire responses revealed that students perceived the activity as motivating, useful, and easy to implement, highlighting the value of incorporating such interactive and innovative methods in chemistry teaching. The results suggest that combining conceptual and visual learning through model-based activities improves students' cognitive and spatial abilities, enabling a deeper and more comprehensive understanding of stereochemistry. The incorporation of these activities, along with IUPAC (International Union of Pure and Applied Chemistry) nomenclature rules for naming stereoisomers, into the regular high school chemistry curriculum represents an effective pedagogical approach that fosters scientific and critical thinking while encouraging active, collaborative, and inquiry-based student participation. Such integration allows students to engage with complex chemical topics more effectively and meaningfully.

As a future direction, stereochemical concepts should be introduced earlier in the high school chemistry curriculum and reinforced in later years. Furthermore, professional development of the teaching staff in high schools on how to present stereochemical concepts in a more effective manner is strongly recommended.

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