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Improvement of students' achievements in organic stereochemistry by active learning using information and communication technologies

Running title: Active Learning and ICT in Organic Stereochemistry Education

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ABSTRACT

Stereochemistry remains a challenging topic for undergraduate chemistry students, often leading to misconceptions and learning difficulties. To improve students' understanding, traditional teaching methods should be complemented by innovative strategies such as interactive learning tools, digital resources, and hands-on activities. This study aimed to identify the main difficulties students face when learning stereochemistry and to evaluate the effectiveness of different pedagogical interventions.

A pre-test assessing key stereochemistry concepts was administered to 24 second-year students at the Institute of Chemistry, Faculty of Science and Mathematics in Skopje, Republic of Macedonia. The results revealed significant challenges, particularly in identifying chiral centers, determining *R/S* configurations, recognizing meso compounds, and understanding *E/Z* isomerism. Students also struggled with the spatial representation of molecules and applying stereochemical rules to structural representations. Targeted teaching activities, including web-based tutorials, physical molecule models, and the HyperChem Professional computer program, were introduced to address there difficulties.

A post-test was then conducted to measure learning gains. Statistical analysis using a paired-samples *t*-test indicated a significant improvement in students' stereochemical knowledge ($p < 0.001$), with an average increase of 30.95% in test scores. These findings demonstrate the effectiveness of interactive and hands-on approaches and underscore the value of multifaceted teaching strategies that integrate digital tools, laboratory activities, and visualization techniques to

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reinforce student learning and bridge the gap between theoretical and practical aspects of stereochemistry.

Keywords: active learning, chemistry teaching, learning difficulties, misconceptions, organic stereochemistry

Introduction

Organic chemistry is a major branch of chemistry, forming the basis for developments in biochemistry, pharmacy, and medicine. and playing a key role in the discovery of new materials with numerous practical applications. As a teaching subject, it covers a wide range of abstract and complex topics because the molecular structure of organic compounds and many phenomena occur at the molecular level and are invisible to the naked eye. To acquire conceptual knowledge, students must learn in all three domains of learning: macroscopic, microscopic, and symbolic (Brown et al., 2012). The gradual introduction of chemical concepts – starting with macroscopic observations before moving on to molecular explanations and symbolic representations – is consistent with the constructivist approach (Taber and Watts, 2000). Despite this, many students find it difficult to represent molecular structures and processes symbolically because they struggle to understand the real structures, molecular interactions, and rearrangements during chemical reactions.

Numerous studies have highlighted that even fundamental terms and concepts in organic chemistry, such as nomenclature, properties, and classification of organic compounds, can be difficult for students to master (Donkoh, 2017; Uchegbu et al., 2017; Anderson & Bodner, 2008; Domin et al., 2008; Hassan et al., 2004). Donkoh (2017) emphasizes the need for curriculum reform to provide a stronger foundation in organic chemistry, while Eticha & Ochonogor (2015) and Dwyer & Childs (2017) report that students often struggle to identify functional groups and write reactions. Laboratory work plays a crucial role in overcoming these difficulties (Uchegbu et al., 2017). However, challenges such as bond polarity, functional group recognition, and stereochemistry remain significant (Hassan et al., 2004; Donkoh, 2017; Nartey & Hanson, 2021; Salame et al., 2019; Salame et al., 2020; Amsad et al., 2019). These challenges highlight the need for targeted teaching strategies that emphasize conceptual understanding, problem-solving, and critical thinking, rather than rote memorization. There are several terms in the literature that refer to misconceptions, including "misconceptions" (Bekkink, 2016; Uce & Ceyhan, 2019) and "alternative concepts" (Garnett et al., 1995; Talanquer, 2008). Misconceptions are defined as ideas, opinions, or understandings that are incorrect because of an incomplete or faulty understanding of a particular term or concept (Leonard et al., 2014). In chemistry, these misconceptions can arise from a variety of sources, including prior knowledge, teaching methods, and the abstract nature of certain chemical concepts. Therefore, it is important to recognize the difficulties and misconceptions that arise in the study of organic chemistry, particularly in the teaching content related to organic stereochemistry. The understanding of organic stereochemistry reflects students' conceptual knowledge of organic chemistry, and it is important to pay more attention to this part. By detecting these errors in time and finding ways to correct and overcome them, teachers enable students to further develop their knowledge on a solid and reliable foundation. Moreover, this approach encourages students to develop their critical and logical thinking.

Stereochemistry is among the most complex topics in organic chemistry, primarily due to the challenges it poses in visualizing three-dimensional (3D) molecular structures and accurately translating them into symbolic representations. This abstract nature is compounded by the fact that 3D molecular arrangements can significantly influence molecular properties and biological activities. As Johnstone (1991) notes, mastering conceptual knowledge in stereochemistry requires harmonizing the macroscopic, microscopic, and symbolic domains of learning. A significant challenge lies in translating 2D structural formulas into 3D models, particularly for molecules with multiple chiral centers (Kumi et al., 2013; Olimpo et al., 2015).

Recent studies have sought to address these difficulties through targeted education strategies, with growing research interest in stereochemistry education (Boukhechem et al., 2011; Milne et al., 2024; Ping et al., 2022; Kusumaningdyah et al., 2023; Barrientos et al., 2024). For example, Schmidt (1992) found that students often restrict their understanding of isomerism to compounds with identical functional groups, a limitation that Miu (2019) addresses by proposing more efficient learning strategies. Studies on stereochemistry education explore various approaches to mitigate difficulties. Researchers such as Obumnenye and Ahiakwo (2013), Durmaz (2018), and Collini et al. (2024) emphasize teaching stereochemical configurations, simplifying 3D structure representation (Tuckey et al., 1991; Salah and Alain, 2016), and utilizing programming tools (Kurbanoglu et al., 2006; Rius et al., 2011).

Web-based tutorials, as demonstrated by Burrmann and Moore (2013) and Iyamuremye et al. (2024), support learning by offering interactive stereochemistry tasks. Innovative teaching methods like games have shown promise in engaging students. Ippoliti et al. (2022) developed "*R/S* Chemistry", a game-based learning tool, while Da Silva Junior et al. (2019) introduced an innovative teaching method using a card game designed to help students learn stereochemical concepts effectively. These methods foster interactive learning environments, enhancing conceptual understanding and problem-solving skills.

Addressing specific challenges, Salah and Alain (2016) advocate testing students' ability to transition between 3D models and 2D representations using tools like Newman and Fischer projections. Similarly, Mistry et al. (2018) recommend web-based tools for constructing 3D models, exploring molecular conformations, and determining the R/S configurations of stereocenters using Cahn-Ingold-Prelog rules. Burrmann and Moore (2013) propose tutorials that extend these capabilities to include *E/Z* isomerism for alkenes. Ultimately, adopting diverse teaching approaches, hands-on experiments, interactive tools, and gamification can help overcome the complexities of stereochemistry, improving students' engagement and comprehension. Similarly, Ippoliti et al. (2022) developed "*R/S* Chemistry", a free, game-based learning tool that engages students in practicing stereochemistry tasks within an interactive environment. Both

approaches aim to enhance student engagement and foster active participation in the learning process.
As can be seen from all this, the problems associated with the study of organic stereochemistry are becoming increasingly important. We have confirmed this through our previous research on the frequency of organic stereochemistry questions in international chemistry competitions (Naumoska & Aleksovska, 2023). Additionally, in our previous research, we investigated high school students' conceptual understanding of this topic and found that students struggle with these concepts, leading to a large number of misconceptions (Naumoska & Aleksovska, 2023). To understand the main reasons for these problems, their impact on the study of organic stereochemistry among undergraduate students, and potential solutions, we conducted the research described in the following section.

Experimental

The aim of the research

The research aimed to evaluate undergraduate chemistry students' knowledge and identify their difficulties and misconceptions regarding key organic stereochemistry concepts after attending the course on this topic. The course utilized PowerPoint presentations, animations, and demonstrations of various molecular models, presented by the teacher. It focused on challenges in understanding conformations and stereochemistry of alkanes and cycloalkanes, recognizing geometric isomerism in alkenes, determining the *R/S* configuration of chiral centers, and identifying meso compounds.
To overcome the detected difficulties and misconceptions, the study also sought to develop targeted instructional methods that actively involve students in the learning process. To enhance understanding, theoretical exercises for students, performed individually or in pairs, were developed using web-based tutorials, programming software HyperChem Professional, and molecular models. The final goal was to foster conceptual change, ultimately improving students' progress in organic stereochemistry.

Research questions included:
1. Are there objective difficulties and misconceptions among students about organic stereochemistry topics?
2. What causes these difficulties and misconceptions?
3. Does the intervention help students overcome these challenges and improve their understanding?

Based on these research questions, the following hypotheses are proposed:
H1: Undergraduate students exhibit significant conceptual difficulties and misconceptions when learning organic stereochemistry, particularly in identifying chiral centers, assigning *R/S* configurations, and recognizing meso compounds.

H2: These difficulties are primarily caused by limited spatial visualization skills, the abstract nature of stereochemical concepts, and insufficient use of interactive or tactile learning tools.
H3: The implementation of targeted pedagogical interventions (including digital tutorials, physical molecular models, and stereochemistry simulation software) leads to statistically significant improvement in students' understanding of stereochemistry.

Research sample

In order to investigate the possible existence of difficulties and misunderstandings, i.e., misconceptions, related to the concepts of stereoisomerism of alkanes and cycloalkanes, *E/Z* and *R/S* stereoisomerism, and determination of meso compounds, a study was conducted at the Institute of Chemistry (Faculty of Science and Mathematics, Skopje, Republic of Macedonia) in the period between November 2023 and February 2024. A total of 24 undergraduate students aged 19–20 years participated in this study. It is important to note that this study was conducted with a relatively small sample (24 students) and lacked a control group. Although this allows for a thorough analysis of conceptual understanding and the effectiveness of the interventions applied, it still limits the generalisability of the results. Therefore, further research with larger samples and control groups is recommended to confirm and expand upon these results.

Design of the research

The pre-test and post-test design is a widely used method in educational research to evaluate the effectiveness of an applied intervention. This design was employed to assess students' understanding of organic stereochemistry topics and address difficulties and misconceptions. The research followed several steps:

1) Administering a pre-test to assess students' knowledge;
2) Analyzing the pre-test data, particularly focusing on the most frequent incorrect answer for each question;
3) Identifying difficulties and misconceptions;
4) Implementing the intervention;
5) Administering a post-test;
6) Analyzing the post-test data and comparing it with pre-test results using JASP.

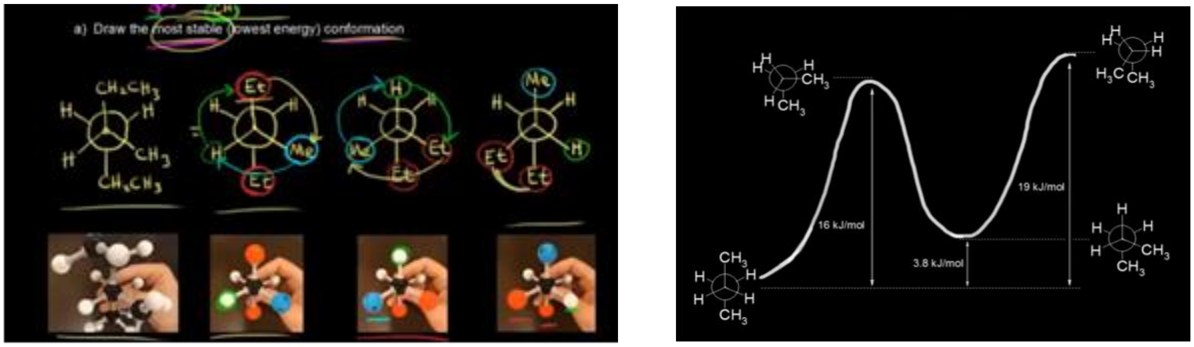
When composing the questions, care was taken to ensure they covered the intended concepts and objectives to be tested, as well as the different domains of Bloom's Taxonomy. To address these varied domains, the questions were assigned different point values (2, 4, and 6 points). Misconceptions were identified through distractor analysis, focusing on the incorrect options chosen by a significant proportion of students. Particular attention was given to distractors selected by more than 20% of students, as these indicate the presence of systematic misconceptions. To ensure content validity, the test questions were reviewed and approved by a professor and an assistant from the Institute of Chemistry.

The pre-test questions were divided into three categories, with each category consisting of four multiple-choice questions. The first four questions were aimed at testing knowledge of the stereoisomerism of alkanes and cycloalkanes. These questions aimed to assess students' ability to apply Newman projection formulas when naming alkanes, to represent structures in their most and least stable conformations, and to graphically represent the change in potential energy as a function of angle of rotation. The second set of questions aimed to assess students' ability to recognize the presence of geometric isomerism in alkenes based on a given structural formula, but also to correctly identify cis/trans, i.e., *E/Z* isomers. The last four questions aimed to assess students' ability to identify chiral centers and determine the *R/S* configuration as well as recognize meso compounds based on a given structural formula.

Intervention phase

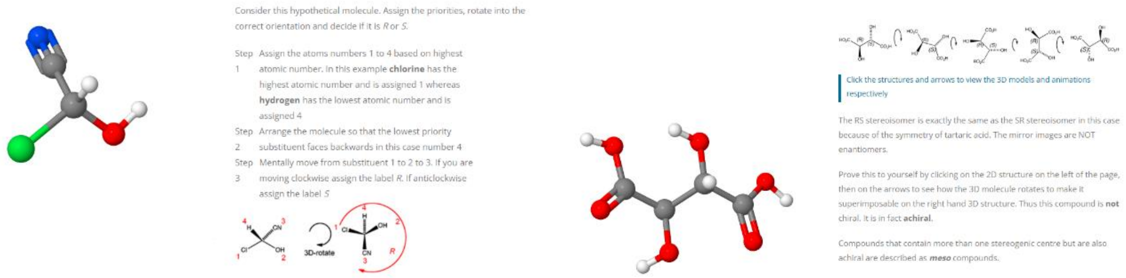
The intervention phase incorporated multiple strategies to support students in mastering stereochemistry concepts. These included:
I. **Web-based tutorials**: The free Khan Academy website (www.khanacademy.org) offers a series of tutorials on cycloalkane stereochemistry, Newman projection formulas, conformational analysis of alkanes, and determination of *R/S* configuration. Selected tutorials have been integrated into theoretical exercises to deepen these topics. The free Chem Tube3D website (www.chemtube3d.com) provided students with opportunities to explore and practice various examples of *R/S* configuration determination.
II. **Computer programs**: The HyperChem Professional program was used to facilitate the determination of stereochemical configurations and recognition of meso compounds.
III. **Molecular models**: While engaging with tutorials and computer programs, students used molecular models to assemble the structures displayed on the screen.

Figure 1 illustrates the various activities carried out during the intervention phase. Figure 1a and Figure 1b show web-based tutorials that helped students better understand the Newman projection formulas and the graphical representation of changes in potential energy as a function of angle of rotation. The remaining images (Figures 1c–1f) depict activities conducted using the ChemTube3D website, physical molecular models, and HyperChem Professional software. Using these tools, students practised determining geometric isomerism in alkenes, identifying chirality and achirality in molecules, assigning *R/S* configurations, and recognizing planes of symmetry in meso compounds.



a) Represent structures in their most/least stable conformations

b) Graphical representation of potential chair energy versus angle of rotation



Consider this hypothetical molecule. Assign the priorities, rotate into the correct orientation and decide if it is *R* or *S*.

Step 1 Assign the atoms numbers 1 to 4 based on highest atomic number. In this example **chlorine** has the highest atomic number and is assigned 1 whereas **hydrogen** has the lowest atomic number and is assigned 4

Step 2 Arrange the molecule so that the lowest priority substituent faces backwards in this case number 4

Step 3 Mentally move from substituent 1 to 2 to 3. If you are moving clockwise assign the label *R*. If anticlockwise assign the label *S*

Click the structures and arrows to view the 3D models and animations respectively

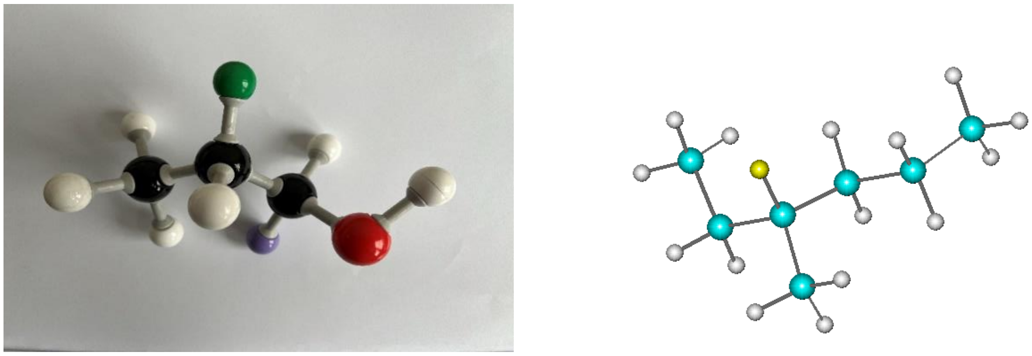
The RS stereoisomer is exactly the same as the SR stereoisomer in this case because of the symmetry of tartaric acid. The mirror images are NOT enantiomers.

Prove this to yourself by clicking on the 2D structure on the left of the page, then on the arrows to see how the 3D molecule rotates to make it superimposable on the right hand 3D structure. Thus this compound is **not** chiral. It is in fact **achiral**.

Compounds that contain more than one stereogenic centre but are also achiral are described as ***meso*** compounds.

c) Determining the *R/S* configuration of chiral centers

d) Recognizing meso compounds



e) Determining the *R/S* configuration of chiral centers using physical molecular models and HyperChem Professional (f)

Figure 1. Activities used during the intervention

After the intervention, a post-test was administered, similar to the pre-test, consisting of 12 questions divided into three categories, with four questions in each category. The purpose of the post-test was to assess whether the intervention helped students overcome difficulties and misconceptions regarding topics in organic stereochemistry. Both tests are provided as supplementary materials.

Results and Discussion

As already mentioned, the students' acquired knowledge in stereochemistry was first assessed using a pre-test. The results of the pretest showed that, with the exception of questions 5 and 7 (each worth 2 points), more than half of the students answered all other questions incorrectly (Table 1). Particular attention was paid to the incorrect answers (distractors), selected by more than 20% of the students, as these indicated the presence of misconceptions regarding specific stereochemical content. According to Gilbert (1977), conceptual understanding can be categorized into four levels:

- Satisfactory Conceptual Understanding (SCU): correct answers given by 75% or more of the students.
- Roughly adequate performance (RAP): Correct answers in the range of 50–74%.
- Inadequate Performance (IP): Correct answers in the range of 25–49%.
- Fairly Inadequate Performance (QIP): Correct answers selected by less than 25% of students.

Table 1. Number of correctly answered (C) and incorrectly answered (I) questions on the pre-test

Number of questions		1	2	3	4	5	6	7	8	9	10	11	12
Number of answers	C	9	4	3	11	13	10	14	8	9	6	7	6
	I	15	20	21	13	11	14	10	16	15	18	17	18
Percentage of correct answers		37.5	16.7	12.5	45.8	54.1	41.7	58.3	33.3	37.5	25	29.2	25
Standard deviation		0.484	0.373	0.331	0.498	0.498	0.493	0.493	0.471	0.484	0.433	0.455	0.433

The results presented in Table 1 support the first hypothesis, which states that students exhibit significant conceptual difficulties in stereochemistry. The low percentage of correct answers across several items (particularly those involving chiral centers, *R/S* configurations, and meso compounds) indicates that these topics pose substantial challenges. The variability in responses, reflected in the standard deviations, further confirms that students have differing levels of understanding, consistent with the hypothesis. Namely, the standard deviations of the responses (correct–incorrect) range from 0.331 to 0.523, which is within the expected range for binary data of this type. These values indicate that students exhibited varying levels of understanding across the questions. Moreover, the distribution suggests that the items were well constructed, neither too difficult nor too easy, allowing for meaningful differentiation in student performance. To identify the reasons behind the low performance, we analyzed the answers for each question.

The purpose of the first question was to assess how well students could apply the rules for naming organic compounds using a given Newman projection formula. Only 37.5% of students answered correctly, while 30% chose the distractor (c). Students often make mistakes when naming compounds using the Newman projection formula because it requires a strong spatial understanding of molecular geometry. Errors occur in identifying the correct relative positions of substituents (e.g., staggered vs. eclipsed conformations) and translating this arrangement into the correct nomenclature. Confusion also arises when priorities are overlooked in naming substituents or assigning configurations. The difficulties in visualizing the 3D structures represented by the Newman projection are likely the primary reasons for the high percentage of incorrectly selected answers, along with probably insufficient understanding of systematic naming rules. These difficulties are consistent with previous reports indicating that students often struggle to visualize three-dimensional structures and correctly apply stereochemical rules (Mistry et al., 2020; Boukhechem et al., 2011; Burrmann & Moore, 2013; Tuckey et al., 1991).

The second and third question assesses of chair conformations of cyclohexane, axial and equatorial positions of substituents, and conformational stability. For the second question, in order to choose the correct structure, the students had to draw all four possibilities offered by their names. A very low percentage of correct answers was obtained here, i.e., a full 16.7% for the second and 12.5% for the third question. For both questions, students chose the incorrect answer- c. Regarding the second question, it is clear that students have difficulties drawing the chair conformation, i.e., the symbolic representation of the structure. They mismatched the *cis/trans* with axial/equatorial positions of the substituents. Students often made errors when selecting the most stable chair conformation because they had difficulty visualizing the 3D spatial arrangement of the substituents, which is evident in the third question. Key errors include misidentifying axial and equatorial positions, failing to recognize steric hindrances caused by large groups in axial positions, and overlooking 1,3-diaxial interactions. In addition, a limited understanding of conformational energy differences between chair inversions can lead to incorrect decisions. These challenges are compounded by the lack of practice in analyzing and predicting the stability of conformations based on substituent interactions.

The final question in this category assessed students' ability to match conformers to specific points on a graph showing the change in potential energy as a function of angle of rotation. The students achieved significantly better results (45.8% correct answers) in comparison with the previous two questions. Students often have difficulty with such diagrams because they cannot relate the molecular conformations to the energy trends. Identifying energy minima (staggered conformations) and maxima (eclipsed conformations) can be particularly challenging. Again, the main difficulty arises because of the lack of ability to visualize the 2D presentation.

The second group of questions was designed to investigate how well students can recognize and correctly identify geometric isomerism in alkenes. The students performed best on this part of the test, but the results are still unsatisfactory. To this end, four questions were designed for each of the two tests, asking students to use structural formulas to determine whether geometric isomerism was present and, if so, whether it was cis/trans or *E/Z*. In addition, for some questions, students were presented with pre-labelled *E/Z* isomers and had to determine which labels were correct or incorrect. In these questions, students often made mistakes when using the *E/Z* system to name alkenes because they had difficulty determining the priority of substituents on each carbon of the double bond according to the Cahn–Ingold–Prelog (CIP) priority rules. Students often struggle with naming structures containing multiple bonds, particularly those involving C-O and C-N bonds, as seen in the fifth and sixth questions. Additionally, they face challenges in recognizing geometric isomerism in alkenes and identifying isomers of a given formula. This difficulty stems from a failure to recognize the limited rotation around a double bond, a key characteristic of isomerism that is essential for understanding geometric isomerism. They may overlook the presence of different substituents on either side of the double bond, which is necessary for geometric isomerism. Confusion arises when multiple substituents or chains are present, making it difficult to identify isomers and assign the correct *cis/trans* or *E/Z* configuration. These challenges reflect common misconceptions reported in the literature, highlighting that students frequently struggle with geometric isomerism and the application of the *E/Z* system (Durmaz, 2018; Miu, 2019; Salame et al., 2019).

The students' scores on the seventh question were the highest on the test. However, some students still thought that geometric isomerism is possible only when two hydrogens are bonded to the same carbon atom in a C=C bond, so they didn't consider tetrasubstituted C=C bonds with four different substituents. The eighth question was actually assessing the ability of the students to recognize the type of isomerism. Surprisingly, the score was low (33% of correct answers), and 42% of the students incorrectly believed that the two compounds were *cis/trans* isomers. This means that they had serious misconceptions in recognizing types of isomerism.

The last group of questions was designed to assess students' ability to identify chiral centers, determine *R/S* configuration, and recognize meso compounds. In the ninth question of the pre-test, 29% of students incorrectly thought that compound V contained a chiral center (answers a and c). This highlights the difficulties students faced in identifying chiral centers, such as recognizing tetrahedral carbon atoms bonded to four different groups. These difficulties often stemmed from limited spatial visualization skills, unfamiliarity with chirality rules, and misconceptions about symmetry or what "different groups" were. Overcoming these problems required focused practice and a solid foundation in stereochemical principles. In the tenth question, students had to identify which structure was different from the others. In order to answer correctly, they had to apply the *R/S* nomenclature system to all given compounds and determine their configurations. However, only 25% of the students gave the correct answer. This shows that a significant proportion of students had difficulty distinguishing the structures based on their symbolic presentation using perspective formulas. Since only a small proportion of students answered this question correctly, it is suggested that many students had difficulty effectively applying the *R/S* system, which is essential for understanding stereochemistry. This difficulty could be due to the challenge of prioritizing substituents around chiral centers, determining the correct orientation of molecules, or unfamiliarity with how to systematically analyze stereoisomers.

Similarly, in the penultimate question, only 29% of students answered correctly. In this case, the students were asked to find which of the given structures has the *S*-configuration. The low achievement level again indicates that many students had difficulty using *the R/S* nomenclature system to assign the correct configuration to the chiral centers. Identifying the configuration can be particularly challenging, especially when dealing with complex molecules with multiple substituents. This difficulty primarily stemmed from a lack of the ability to visualize the three-dimensional arrangement of atoms around the chiral center and the challenge of following the steps required to prioritize the substituents according to the Cahn-Ingold-Prelog rules. Overall, this difficulty emphasized the need for further instruction and practice in the correct application of stereochemical conventions.

In the final question, only 25% of students correctly identified the structure representing a meso compound. This suggested that most students had difficulty understanding the key features of meso compounds, which contain chiral centers but are achiral due to an internal plane of symmetry. Meso compounds present a unique challenge because, while they exhibit stereoisomerism, their internal symmetry renders them optically inactive. Identifying these compounds requires a thorough understanding of molecular symmetry and the specific arrangement of substituents around chiral centers. The low success rate on the corresponding questions indicates that many students have difficulty distinguishing meso compounds from other stereoisomers, such as enantiomers, or recognizing the symmetry responsible for achirality, even when chiral centers are present. This emphasized the need to better communicate the characteristics of meso compounds, their identification and the evaluation of symmetry in molecules.

The pre-test results indicated that serious intervention was necessary to improve the students' knowledge. To achieve this goal, students were directly and actively involved in the learning process. They were taught using computer tutorials and programs, while simultaneously using molecular models and working individually or in pairs. Previous studies support the effectiveness of such approaches, demonstrating that integrating ICT tools, interactive molecular models, and guided hands-on activities can enhance students’ conceptual understanding and spatial reasoning in stereochemistry (Burrmann & Moore, 2013; Rius et al., 2011; Kusumaningdyah et al., 2024; Da Silva Junior et al., 2019).

These findings are consistent with Hypothesis 2, which attributes students’ difficulties in stereochemistry to limited spatial reasoning skills and the abstract nature of the concepts involved. The low performance on items requiring identification of chiral centers and assignment of *R/S* configurations suggests that traditional instruction may not sufficiently support the development of three-dimensional thinking.

After various instruments were used to eliminate difficulties and misconceptions, the post-test, which consisted of questions that checked the same concepts as the pre-test was conducted. The results obtained were compared with the results of the pre-test using the *t*-statistic (paired samples *t*-test) from the statistical software package JASP. The results obtained were shown in Table 2.

Table 2. Comparison of Pre-Test and Post-Test Results: N-Number of students; $\bar{x}$- Average success of the group; s-Standard deviation; $\Delta\bar{x}$- Difference between the average successes; t: t-test value; t_{crit}-Critical value of the t-test; df-Degrees of freedom; p- p-value

Test	N	$\bar{x}$ /%	s	$\Delta\bar{x}$ /%	Cohen's d	t	t_{crit}	df	p
Pre-test	24	34.72	12.07	30.95	2.46	13.4	2.07	23	0.001
Post-test	24	65.67	13.1						

The results presented in Table 2 strongly support Hypothesis 3. As shown in Table 2, students performed better on the post-test than on the pre-test. The statistical significance of this improvement can be determined from the t-test result at the 5% significance level. This test compares the means to evaluate the validity of the null hypothesis, which assumes no significant difference between the two sample means. The results show that $t > t_{crit}$ and $p < 0.001$, indicating a statistically significant difference and suggesting that the improvement is likely due to the applied activities. In addition to the statistically significant improvement, the magnitude of the learning gains was assessed using Cohen's d, which was calculated as 2.46. According to established guidelines, this represents a very large effect size (Cohen, 1988), indicating that the intervention had a substantial and meaningful impact on students' understanding of stereochemistry. These findings are consistent with previous studies demonstrating that targeted instructional strategies, including visualisation tools and structured exercises, can significantly improve students' performance and conceptual understanding in stereochemistry (Barrientos et al., 2024; Mistry et al., 2020; Kusumaningdyah et al., 2024). Figure 2 shows the group's average results for each pre-test and post-test question.

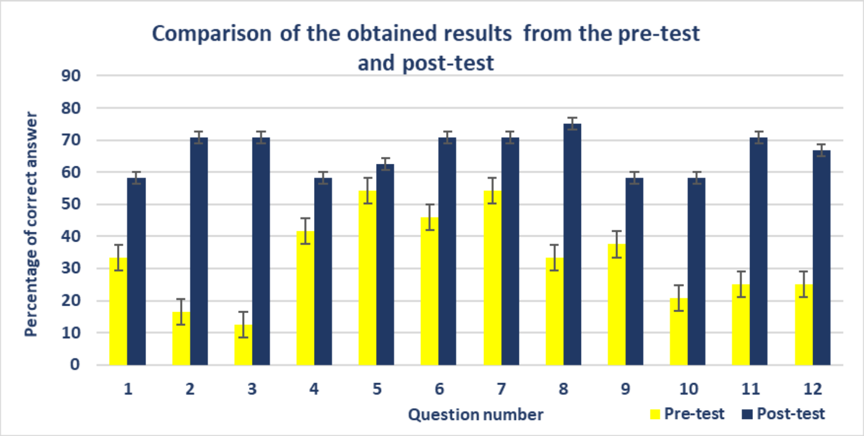


Figure 2. Comparison of the results achieved from the pre-test and post-test

As can be seen in Figure 2, the results of the post-test show a remarkable improvement in the students' performance, with error bars representing the standard deviation,demonstrating that the applied activities effectively improved their understanding of stereochemistry. Specifically, the activities helped students gain a better understanding of isomerism in alkenes and gave them the tools to better analyze and interpret stereochemical concepts.

To assess whether and to what extent students' performance improved after the intervention, a detailed comparison of results before and after the test was conducted for each student. Figure 3 not only highlights the extent of improvement but also provides valuable insight into the intervention's overall effectiveness in addressing the challenges and misconceptions associated with stereochemical concepts. The comparative approach ensures a clear assessment of progress and identifies areas of significant conceptual change.

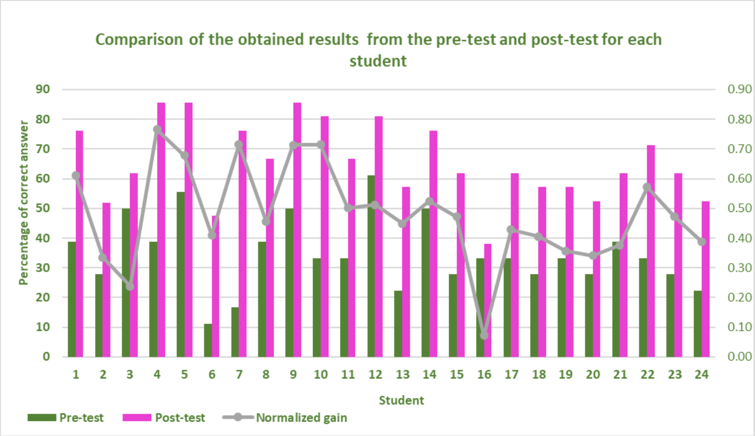


Figure 3. Comparison of the results achieved from the pre-test and post-test for each student Figure 3 shows that all 24 students demonstrated a significant improvement in their performance on the post-test, after the applied intervention, compared to their performance on the pre-test. The normalized gain (g) calculated for each student further quantifies this improvement, showing that most students achieved moderate to high gains, while only a few achieved lower gains. This consistent progress across the group underlines the effectiveness of the intervention strategies used. The activities implemented during the intervention appear to have successfully addressed and corrected the difficulties and misconceptions associated with stereochemical concepts. Furthermore, this finding underscores the value of targeted instructional approaches and the application information and communication technologies (ICT) to improve student understanding and facilitate conceptual change in difficult areas of organic chemistry.

Conclusion

Based on the results, several conclusions can be drawn. The pre-test results demonstrated that when students are passively taught organic stereochemistry through traditional instruction, even when supported by computer animations or molecular models, their achievements remain unsatisfactory. The analysis of the pre-test responses indicated that the main learning difficulties stem from students' limited spatial visualization skills and their inability to connect 3D molecular structures with their 2D representations, such as Newman and perspective formulas. Additionally, students struggle to apply the Cahn-Ingold-Prelog rules for assigning priorities, especially with complex substituents.

After implementing an intervention based on active learning and ICT (e.g., computer tutorials and programs), students' conceptual understanding of stereochemistry significantly improved. This improvement, confirmed by a statistical analysis, highlights the effectiveness of engaging students directly in visual and manipulative learning activities.

The findings emphasize the importance of incorporating visualization-based and technology-supported methods into the organic stereochemistry curriculum to promote deeper conceptual understanding. Furthermore, the study suggests that teacher-training programs should include targeted preparation to develop students' spatial reasoning skills and to integrate ICT resources effectively into stereochemistry instruction.

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Conflict-of-Interest Statement

The authors declare that they have no conflict of interest.

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