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Teaching Stereochemistry with Multimedia and Hands-On Models: The Relationship between Students' Scientific Reasoning Skills and The Effectiveness of Model Type

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This paper presents an analysis of the use of multimedia and hands-on models on university students' understanding of stereochemistry. The relationship between students' scientific reasoning skills and their understanding of stereochemistry was also determined. Two groups of second-year chemistry students from the State University of Malang taking organic chemistry for the 2020/21 academic year participated in this study. One group of students experienced stereochemistry teaching using multimedia models and the other hands-on models as the learning medium. Lawson's Classroom Test of Scientific Reasoning and Short-Answer Stereochemistry Test were applied. The former was deployed to measure students' scientific reasoning skills, while the latter was used to test their understanding of stereochemistry. The results revealed that the students' scientific reasoning skills were significantly below the expected standard, falling in the low category. Students with high scientific reasoning skills exhibited a better understanding of stereochemistry than those with low levels. Both multimedia and hands-on models revealed an equal contribution towards students' understanding of stereochemistry. Also, it suggests that multimedia models tend to favour students with high scientific reasoning skills, while hands-on models favour those with low skills.

Keywords: stereochemistry, pictorial representation, physical model, models, and modelling

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Poučevanje stereokemije z multimedijo in s praktičnimi modeli: odnos med zmožnostmi naravoslovnega mišljenja pri študentih in učinkovitostjo vrste modela

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Članek predstavlja analizo uporabe multimedijskih in praktičnih modelov pri razumevanju stereokemije pri univerzitetnih študentih. Ugotovljena je bila tudi povezava med zmožnostmi naravoslovnega mišljenja študentov in njihovim razumevanjem stereokemije. V tej študiji sta sodelovali dve skupini študentov drugega letnika kemije z državne univerze v Malangu, ki so bili v študijskem letu 2020/21 študentje predmeta organska kemija. Ena skupina študentov je izkusila poučevanje stereokemije z uporabo multimedijskih modelov kot učnega medija, druga pa praktičnih modelov kot učnega medija. Uporabljena sta bila Lawsonov test naravoslovnega mišljenja za uporabo v razredu in test iz stereokemije s kratkimi odgovori. Prvi je bil uporabljen za merjenje zmožnosti naravoslovnega mišljenja, drugi pa za preverjanje razumevanja stereokemije pri študentih. Rezultati so pokazali, da je bila stopnja zmožnosti naravoslovnega mišljenja študentov precej pod pričakovanim standardom in se uvršča v nižjo kategorijo. Študentje z višjo stopnjo zmožnosti so pokazali boljše razumevanje stereokemije kot učenci z nižjimi stopnjami zmožnosti. Multimedijski in praktični modeli so enako prispevali k razumevanju stereokemije pri študentih. Študija prav tako kaže, da so multimedijski modeli primernejši za študente z visokimi stopnjami zmožnosti naravoslovnega mišljenja, medtem ko so praktični modeli primernejši za študente z nižjimi stopnjami zmožnosti naravoslovnega mišljenja.

Ključne besede: stereokemija, slikovna predstavitev, fizični model, modeli, modeliranje

Introduction

Stereochemistry involves geometric isomerism, molecular conformation, and chirality. It is fundamental to an understanding of organic chemistry and plays an important role in other disciplines, including pharmacy, biochemistry, molecular biology, biotechnology, and medicine. For example, many drugs are chiral, with only one enantiomer providing the desired effect; in some cases, the other form is detrimental. Molecular chirality can also play a part in food chemistry, where different enantiomers may impart a different taste or smell (Solomons et al., 2017). Chirality is also important in the field of heterogeneous catalysis, especially on surfaces. Therefore, understanding stereochemistry is essential for undergraduate chemistry students. Regardless of the importance of this topic, its appreciation is challenging for university students because chemistry textbooks are mostly presented in two-dimensional (2-D) representations (Abraham et al., 2010). Drawing and visualising molecules in fixed orientations and identifying the stereochemistry of those molecules is a difficult task for many students (Dickenson et al., 2020). A study involving prospective chemistry teachers revealed some misconceptions in the area of stereochemistry (Durmaz, 2018). Using three-dimensional (3D) molecular structures as building blocks for the understanding of stereochemistry is a spatial challenge for many students (Stull et al., 2012; Wu & Shah, 2004).

Efforts to improve students' understanding of stereochemistry can be carried out in several ways, including using models and modelling involving hands-on/physical models or molecular modelling. Teaching with the aid of multimedia in which pictorial and verbal representations are presented simultaneously (Mayer, 2008; Richter et al., 2016) color coding in static or dynamic forms (Mayer, 2008) has been a preferable learning approach over the years (Çeken & Taşkın, 2022). Multimedia learning contributes to cognitive development according to the following brief process. Multimedia contains words and/or pictures that are interpreted by students' sensory memory. The memory works to further process and organise the verbal and pictorial representations. Next, students store it in their long-term memory by combining the pictures and words with their prior knowledge (Mayer, 2008). However, Çeken & Taşkın (2022) found that multimedia was mostly implemented in the area of STEM education and suggested employing multimedia in other learning environments. Fatemah et al. (2020) applied mobile software and virtual tools to narrow the performance gap between students with different spatial abilities. Previous studies strongly recommended employing computational modelling to improve students' understanding of stereochemistry (Durmaz, 2018). The virtual model provides a better opportunity to manipulate the 3D models and translate 2D to 3D representations (O'Brien, 2016).

Molecular models utilising 3D have been extensively applied in some stereochemistry teaching (Upton, 2001) and other chemical molecule modelling classes (Bernard & Mendez, 2020). Using appropriate visualisation tools, the 3D models can be altered to enable the selection of pertinent viewpoints. It is possible to write line diagrams directly on top of these 3D models with the help of an overlay annotation tool (O'Brien, 2016). The study by Bernard & Mendez (2020) uncovered another advantage of 3D models over their 2D counterparts. The 3D model allowed students to create a personalised model. Another study utilised 3D printing to create a 2D model of NMR spectra and HPLC chromatograms to assist students' understanding (Jones et al., 2021). These novel physical models aid students in grasping the complicated information offered in multidimensional spectra and chromatograms, especially those who learn best through visual and/or tactile means (Jones et al., 2021). However, the unfamiliarity of students with the modelling tool is sometimes an issue (Upton, 2001), particularly in transforming 2D to 3D models (Kok, 2020). Cognitive processes of spatial visualisation have been linked to the ability to create 3D pictures of an item from its 2D views, as confirmed by research by Kösa & Karakuş (2018) and Rodriguez & Rodriguez (2017). In addition, It is difficult to model even tiny molecules with any degree of accuracy using 2D drawing software, let alone 3D (Bernard & Mendez, 2020).

Comparisons of the effectiveness of the two models (virtual and hands-on) towards students' understanding of stereochemistry are limited (Casselman et al., 2021). Several studies utilised 3D printing (Dickenson et al., 2020), hands-on laboratory work (Taagepera et al., 2011), multimedia technology (Ugliarolo & Muscia, 2012), interactive computer games (Júnior et al., 2017) and stereochemistry physical games in the form of a boardgame (Júnior et al., 2019) to assist students in understanding stereochemistry concepts. However, they did not compare the effectiveness of the two selected tools. For example, Dickenson et al. (2020) conducted a 3D printing workshop to improve students' fluency in drawing stereochemistry structures and other related entities (chirality, stereoisomerism, enantiomer, diastereomers) and their understanding was measured before and after the workshop. Thayban et al. (2021) compared hands-on and virtual models in the teaching of symmetry. Casselman et al. (2021) contrasted the effects of teaching organic chemistry with virtual versus physical Embodied Learning Tools (ELTs) on students' understanding of stereochemistry. Web-based tools with virtual-3D have also been applied to assist students in transforming Newman projections (the conformation of the chair and assigning R/S labels) to a

2D dashed/wedged structure (Mistry et al., 2020). Elford et al. (2022) and Habig (2020)first representations are examined from a science educational and instructional psychology perspective. After giving a short overview of AR in general and how it can be delineated from virtual reality (VR employed augmented reality (AR) to provide a 3D virtual environment for teaching stereochemistry. Another study incorporated animation and hands-on models to improve students' understanding of organic chemistry (Al-Balushi & Al-Hajri, 2014). The use of multimedia is expected to assist students in visualising chemistry concepts (Rodrigues & Gvozdenko, 2011) Abraham et al. (2010) applied computer modelling and a handheld ball-and-stick model to assist students' understanding of stereochemistry. Although this study compared computer and hands-on models, it did not relate to students' scientific reasoning skills (SRS).

SRS and critical thinking are the core competencies that students must harbour for their future careers (Dowd et al., 2018)but little empirical evidence exists regarding the interrelationships between these constructs. Writing effectively fosters students? development of these constructs, and it offers a unique window into studying how they relate. In this study of undergraduate thesis writing in biology at two universities, we examine how scientific reasoning exhibited in writing (assessed using the Biology Thesis Assessment Protocol. SRS correlate with students' ability to carry out observations, investigations, and modelling (Bunce et al., 2017; Krell et al., 2020). Referring to Piaget's theory, SRS is related to the last development of the cognitive stage, which is formal operational (Babakr et al., 2019). The development of students' SRS correlated to cognitive and emotional involvement in augmented reality-based instruction (Chang et al., 2018). Students' ability to predict and explain chemical phenomena is affected by their understanding of chemical as well as mathematical modelling (Lazenby et al., 2019). According to Lawson, scientific reasoning plays a central role in producing scientific knowledge (Bao et al., 2022). Stereochemistry concepts (chirality, enantiomer, and symmetry) are mostly represented by models to assist students in better understanding them. Therefore, efforts to reveal the relationship between students' SRS and their understanding of stereochemistry deserve attention.

Models and Modelling in Science and Chemistry Education

According to The Oxford English Dictionary, a model refers to a three-dimensional representation of a smaller object scale'. The use of the term 'model' can be expressed as the simplification of natural phenomena (e.g., an idea, system, situation, or process) and used as the basis for explaining and understanding them (Bodner et al., 2005; Gilbert, 1997; Hallström & Schönborn, 2019); therefore, it facilitates scientific inquiry (Ingham & Gilbert, 1991). Chamizo (2013) reviewed and proposed various definitions of models and finally agreed with the previous definition that a model represents entities (ideas, phenomena, objects, processes, and systems) connecting theory and phenomena. A model can also be presented in a mathematical expression, such as the relationship of volume, temperature, and the number of gas molecules in gas laws (Bodner et al., 2005). At the same time, modelling refers to constructing a model for a particular system (Bodner et al., 2005) that serves as a thinking and communicative tool for predicting, explaining, and communicating scientific phenomena (Chamizo, 2013).

It has been widely accepted that chemical concepts are mostly explained in the sub-microscopic and symbolic models due to their abstract characteristics. Therefore, in chemistry, we deal with several phenomena interpreted and communicated through certain models (Justi & Gilbert, 2003). Dalton's atomic model has been the pioneer for how the physical model contributes to the progress of chemical knowledge, followed by other chemists' findings, including Kekulé, Van't Hoff, Pauling, Watson and Crick (Justi & Gilbert, 2003). Using a molecular model facilitates the prediction of chemical behaviour and structural and spatial arrangement, particularly in topics such as stereochemistry (Francoeur, 1997, 2000).

Understanding modelling in chemistry teaching and learning is essential for chemistry educators to recognise the most appropriate model to apply in their teaching (Sjöström et al., 2020). Chemistry educators are expected to understand the nature of the model, construct an appropriate model, utilise the model in chemistry teaching and conduct modelling activities in their teaching (Justi & Gilbert, 2003). In another study, Savec et al. (2006) investigated both prospective and in-service chemistry educators' opinions regarding the role of models and modelling in chemistry and revealed that they were acutely aware of its importance. In line with the increasing deployment of new technologies, such as visualisation, animation, and other computer simulations in the educational sector, the technological literacy of teachers and educators has also increased (Ferk et al., 2003).

Studies involving the use of models and modelling in chemistry have been carried out on many topics, including solid-state of matter (Devetak et al., 2010), revealing students interacted with their own-physical model superior to those with the virtual model and teacher-demonstrated physical model. Regarding retention, students remembered the theory when they had constructed their own either physical or virtual models rather than using teacher-demonstrated ones. Fried et al. (2019) also revealed an improvement in students' motivation and understanding of chemistry when they used student-generated models in organic chemistry and computer-generated models in teaching. The combination of practical work and computer modelling also improved students' performances in crystallography (Daaif et al., 2019). Beck et al. (2020) investigated how students apply models to understand molecular vibrations and rotations of molecules. In other studies, laboratory modelling by asking students to draw the decay of radioactive elements effectively uncovered their misconceptions of radioactive decay and half-lives (Yeşiloğlu, 2019). These studies confirm that models and modelling are useful tools for improving students' understanding and revealing misconceptions.

Students' comprehension of models and modelling (Justi & Gilbert, 2003) is the key aspect of the next standard of science (Guy-Gaytán et al., 2019). Chemistry students frequently use existing models in many topics, including gas laws, the kinetic theory, the theory of collision, the steric effect and others, but they do not directly involve in constructing and evaluating a model (Bodner et al., 2005). Considering this, we provide ample opportunities for students to be actively involved in modelling the stereochemistry concepts.

Research problem and question

Providing appropriate learning tools for teaching stereochemistry has been a priority for some time; however, despite this, many students still find the topic challenging. The main objective of this study was to examine the effect of multimedia and hands-on models on students' understanding of stereochemistry. In addition, the relationship between students' understanding and scientific reasoning skills was explored. The result of this study could be the basis for finding the optimum learning medium for teaching stereochemistry.

Method

Pre-tests and post-tests were implemented for each intervention in this study, with two separate groups of students. One group used hands-on models (comparison group), and the other used multimedia models (experimental group) in teaching and learning stereochemistry. In some literature (Casselman et al., 2021), hands-on models are named 'physical models'. Therefore, the terms 'hands-on' and 'physical' are used interchangeably in this paper.

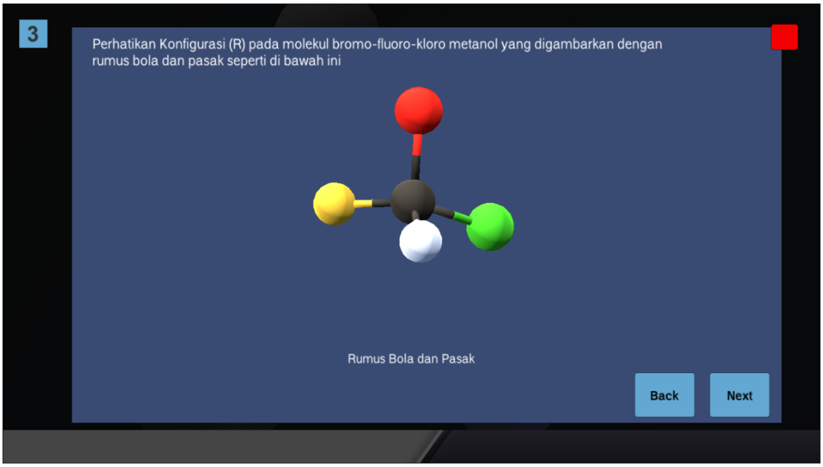
Participants

This study involved 59 second-year chemistry education students from Universitas Negeri Malang taking the Organic Chemistry I class. The students were, on average, 22 years old (*SD* = 2.0). They all learned chemistry in secondary school for three years, covering general and organic chemistry concepts. They also covered concepts helping to understand stereochemistry, such as chemical bonding, molecular geometry, and fundamental concepts in organic chemistry, specifically nomenclature, structure, and reaction mechanisms. The students were divided into two groups, with 29 students for the multimedia-models group and 30 for the hands-on model group. From this point and beyond, students experiencing stereochemistry teaching with a multimedia model are labelled STwM, while those using the hands-on model are labelled STwC.

Examples of multimedia and hands-on models are provided in Figures 1 and 2. The multimedia model displayed in Figure 1 was created in a computer program using Unity3D and Blender software. The model can display a three-dimensional representation of the molecules.

Figure 1

Example of the multimedia model in this study (translation provided)

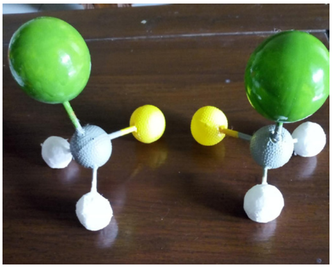


Perhatikan Konfigurasi (R) pada molekul bromo-fluoro-kloro metanol yang digambarkan dengan rumus bola dan pasak seperti di bawah ini

The English translation for the question in Figure 1 is 'look at the (R) configuration of bromochlorofluoromethane that is displayed as a ball and stick model below'. (*Rumus Bola dan pasak* means ball and stick model). Figure 1 displays the R configuration of bromochlorofluoromethane CHBrClF as a ball and stick model. The 3-D model allowed students to physically manipulate the object to view the different arrangements. As shown in Figure 2, the hands-on 3D model is formed from a plastic ball and straws created by students.

Figure 2

Example of the hands-on model in this study



Research Design

This study employed a pre-test-post-test two-treatment design (Cohen et al., 2018). Before embarking on stereochemistry teaching, students' SRS ability was analysed using the CTSR instrument. Students' responses were the basis for classifying them as having a high or low level of SRS. Students in both classes (STwM and STwC) were divided into groups and labelled as students with high and low SRS (Table 1).

Table 1

Pretest-posttest two treatment design of the study

SRS level	Multimedia class (STwM)	Hands-on model class (STwC)
High	X_{111}	X_{121}
Low	X_{112}	X_{122}

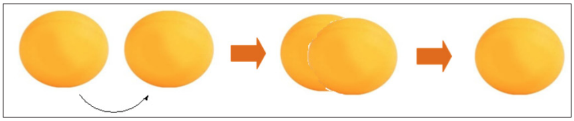
X_{111} and X_{112} were labelled for STwM students with high SRS and low SRS levels, respectively, while X_{121} and X_{122} were for high and low SRS levels among STwC students. The labels are only applied for research purposes to be more recognisable when analysing the data. Both high and low SRS levels were mixed in stereochemistry teaching and experienced the same learning environment based on applied learning media. The teaching approach for STwM and STwC classes was the same (guided discovery model), except for the learning media. The steps of guided discovery in this study adopted the model proposed by Eggen & Kauchak (2012) as follows.

1. Introduction phase

In this phase, the concepts to be discussed are related to previously studied concepts. For example, when discussing 'chirality and enantiomer', students were reminded of structural and geometric isomerism. Then, students were given an analogy question to introduce students to the subsequent topic. Below is the typical question provided in this phase. *Figure 3 below portrays two mirrorable spherics. Do you think the two spherics are superimposable mirror images?*

Figure 3

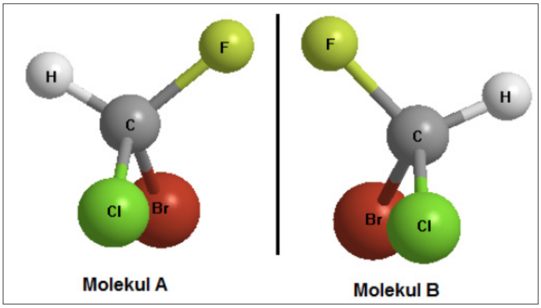
Example of a mirrorable object presented in the introduction phase



2. Open-ended question

The learning model for STwM and STwC groups was applied in this phase. Students were asked to think and express their opinion regarding the follow-up questions. *Figure 4 below is an example of a question provided in this phase. Do you think that the B molecule (molekul B) mirrors the A molecule (molekul A)? Are the two molecules superimposable?*

Figure 4



Example of the mirrorable object presented in the open-ended phase

Students then explored the possible answer to the question using the assigned teaching materials, including the learning media. STwM applied the multimedia model, while the STwC did so with the hands-on model.

3. Convergent phase

In this phase, the lecturer explained the correct answer for the questions given in the previous phase, correcting any misunderstandings that occurred and providing any other necessary explanations of the topics.

4. Closure and application phase

In this phase, some additional questions were given to assess the extent to which students understood the topic.

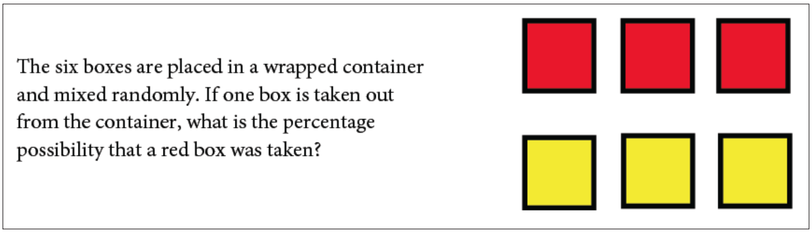
Instruments and Data Analysis

Data in this study cover students' scientific reasoning skills, initial ability, and understanding of stereochemistry after the intervention. Students' scientific reasoning skills (SRS) in the two groups were measured and categorised as those with higher scientific reasoning skills and those with lower scientific reasoning. Students' scientific reasoning skill was measured using the Classroom Test of Scientific Reasoning (CTSR) developed by Lawson (1978), consisting of 24 multiple-choice questions. Following the criteria of Lawson (2004) thus arguments used in their test require sub-arguments to link the postulate under test with its deduced consequence. Science is HD in nature because this is how the brain spontaneously processes information whether it basic visual recognition, every-day descriptive and causal hypothesis testing, or advanced theory testing. The key point in terms of complex HD arguments is that if sufficient chunking of concepts and/or reasoning sub-patterns have not occurred, then one's attempt to construct and maintain such arguments in working memory and use them to draw conclusions and construct concepts will "fall apart." Thus, the conclusions and concepts will be "lost." Consequently, teachers must know what students bring with them in terms of their stages of intellectual development (i.e., preoperational, concrete, formal, or post-formal, students' SRS was categorised as preoperational (0–9 correct answers), concrete (10–14 correct answers), formal (15–19 correct answers), or post-formal (20–24 correct answers). Students with preoperational and concrete levels are attributed to lower SRS, while those with formal and post-formal levels are higher SRS.

Students' understanding of stereochemistry was revealed using ten short answer questions (SAST). Examples of questions from the two instruments are displayed in Figures 5 and 6, while the complete instruments are available on request. Pre-test and post-test questions were used to investigate students' understanding of stereochemistry in the two groups. However, students' scientific reasoning was measured only in the pre-test.

Figure 5

Example of a question of the CSTR instrument

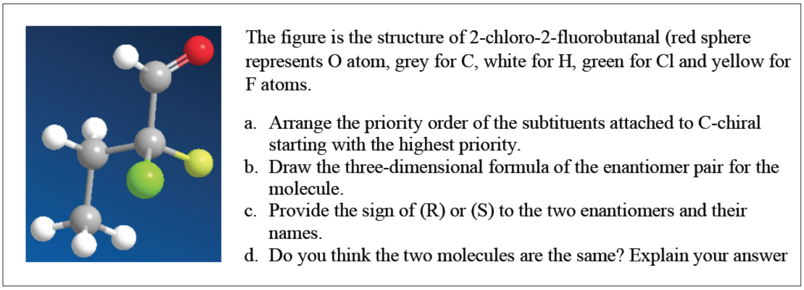


The six boxes are placed in a wrapped container and mixed randomly. If one box is taken out from the container, what is the percentage possibility that a red box was taken?

Figure 5 above depicts the example of a question in the CSTR instrument to measure students' scientific reasoning skills. This question is followed by another question asking the reason for their answer. Meanwhile, Figure 6 displays an example of a question of the SAST instrument to measure students' understanding of stereochemistry. The question is in the Indonesian language but is provided in English on this page for international readers. As mentioned above, the complete instruments are available on request.

Figure 6

Example of a question about the SAST instrument



The figure is the structure of 2-chloro-2-fluorobutanal (red sphere represents O atom, grey for C, white for H, green for Cl and yellow for F atoms.

a. Arrange the priority order of the subtituents attached to C-chiral starting with the highest priority.
b. Draw the three-dimensional formula of the enantiomer pair for the molecule.
c. Provide the sign of (R) or (S) to the two enantiomers and their names.
d. Do you think the two molecules are the same? Explain your answer

Non-parametric statistical procedures, including Rank-Spearman Correlation and the Mann-Whitney U test, were employed to measure the correlation between students' SRS and understanding of stereochemistry and the difference between the two groups. Prerequisite tests were applied, including Levene's Test for homogeneity and the Shapiro-Wilk for normality test. The results showed that the data were not normally distributed and not homogenous, leading to the use of the non-parametric procedure above.

Results and Discussion

The Students' Scientific Reasoning Skills (SRS)

The results of Students' Scientific Reasoning Skills measurements (SRS) are provided in Table 2.

Table 2
Students' SRS Scores

Score	Number of Students	%	SRS Level
0–9	16	29.63	Concrete
10–14	19	35.18	Low Formal
15–19	11	20.37	Upper Formal
20–24	8	14.81	Post Formal

The results indicate that the smallest percentage of students (14.81%) possess the highest SRS level, *post-formal.* Students with *low formal* and *concrete* SRS levels are the highest in number, with 35.18% and 29.63%, respectively. These percentages imply that the majority of second-year chemistry students hold inadequate SRS levels. This confirms the previous finding that most promising science teachers demonstrate a low SRS (Zulkipli et al., 2020). Piaget's theory states that people develop their highest stage of cognitive development, the formal operational stage, at the age of 11 (Babakr et al., 2019). However, Lazonder et al. (2021) found that the level of scientific reasoning of people of the same ages could develop differently. Even some adult people have not reached this formal reasoning stage (Martin et al., 2010). These students' low scientific reasoning skills should be taken into account in further chemistry teaching. Studies involving university students from the first to fourth years revealed a small correlation between university experiences (how many years they have been in university) to students' SRS (Ding et al., 2016). This paper will only describe how these SRS categories relate to students' understanding of stereochemistry between the STwM and STwC classes. *Concrete* and *low formal* levels are both considered as the low SRS category, while *upper formal* and *post formal* are the high SRS category.

Students' initial ability and the use of multimedia and hands-on models in stereochemistry teaching

The effect of teaching stereochemistry using multimedia and hands-on models is demonstrated by the difference in average scores between the STwM and STwC classes. Table 3 outlines the average marks of the two classes for the pre-test and post-test exercises.

Table 3

The average scores (out of 100) of STwM and STwC classes in SAST before and after the course in stereochemistry using different molecular models

Class	Number of Students	Score for pre-test		Score for post-test	
		$\overline{X}$	*SD*	$\overline{X}$	*SD*
STwM	27	8.2	5.4	58.9	17.4
STwC	27	9.8	7.4	54.9	9.2

The table shows that students' marks for the pre-test are much lower than for the post-test, which is understandable because the pre-test was carried out before the teaching of stereochemistry to the two classes. Students' prior knowledge of stereochemistry is mainly obtained from their secondary school chemistry lessons and is very basic. In this university, fundamental organic chemistry concepts are not covered in basic or general chemistry. The correct answers were mostly found for questions about isomeric structures and cis- and trans-geometric isomerism. They mostly failed to answer questions regarding optical isomers, molecular chirality, diastereomers and mesosomers. Some students also struggled to distinguish between geometric isomers in cyclic compounds and alkenes.

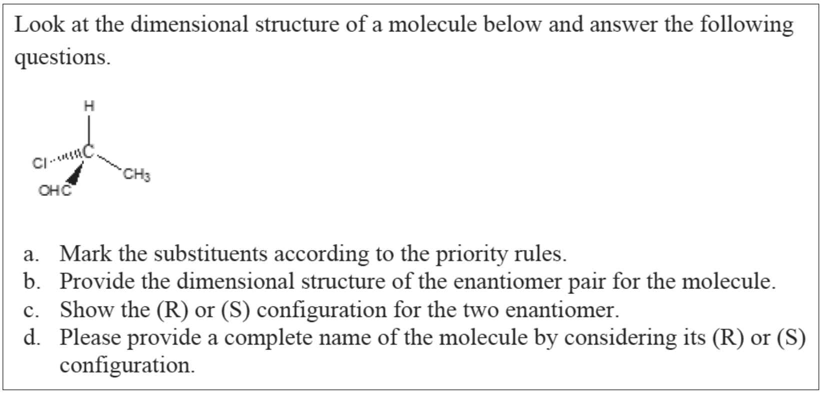
The pre-test aimed to determine students' initial ability in STwM and STwC classes before embarking on stereochemistry teaching. Although the STwM (8.2) mark was slightly lower than that for STwC (9.8), the difference is insignificant. Therefore, it can be concluded that both classes harboured the same level of ability and prior knowledge regarding the topic implying an acceptable interpretation that the use of multimedia and hands-on models will determine the post-test outcomes.

Table 2 also shows that the STwM demonstrated a higher mark average (58.9) than the STwC class (54.9). However, the difference is very small and is not statistically significant, as confirmed by the Mann-Whitney test with a

p-value of 0.257. Therefore, it can be concluded that the use of multimedia and hands-on models in stereochemistry teaching contributed equally to supporting students' understanding. This finding is opposite to the study in the area of solid-state matter in which students who constructed their physical model (equivalent to the hands-on model in this study) demonstrated a better performance than those using virtual models (Devetak et al., 2010). Meanwhile, another study revealed that students from all educational levels demonstrated different approaches to different models. Although students mostly favour hands-on representations over virtual ones, university and secondary school students demonstrated a better performance when using the three-dimensional virtual or computer-generated models, whereas primary school students favoured physical 3D models (Ferk et al., 2003).

Students' post-test average scores for the two classes show that their understanding of stereochemistry is still weak even after deploying multimedia and hands-on models. An analysis of students' attempts to answer one specific question is given below for the example shown in Figure 7.

Figure 7
Example of the question for SAST



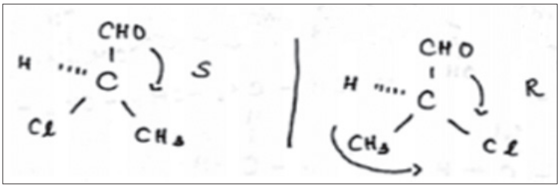
Look at the dimensional structure of a molecule below and answer the following questions.

a. Mark the substituents according to the priority rules.
b. Provide the dimensional structure of the enantiomer pair for the molecule.
c. Show the (R) or (S) configuration for the two enantiomer.
d. Please provide a complete name of the molecule by considering its (R) or (S) configuration.

Figure 8 shows that many students failed to apply the priority order of the substituents as explained in the priority rules of Cahn-Ingold-Prelog. They considered CHO as the priority instead of Cl. This inability led to the students' errors in determining the R or S configuration. Additionally, students' inability to visualise a three-dimensional unit could have contributed to this error. Difficulty in determining R and S configurations was also found in previous studies (Durmaz, 2018).

Figure 8

Example of students' difficulty in determining the (R) and (S) configuration

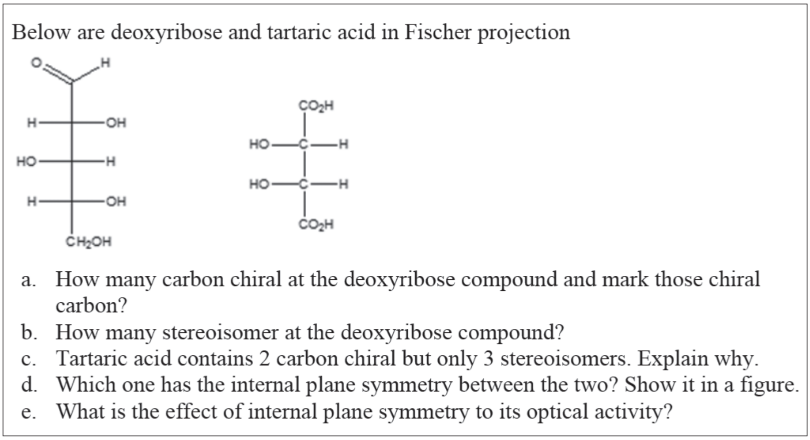


The relationship between SRS and students' understanding of stereochemistry

The relationship between students' SRS and their understanding of stereochemistry can be seen by comparing the average scores of the two groups in answering the SAST questions. For students with high SRS, the score of the stereochemistry test of STwM (76.6) is higher than that for STwC (68.9). In contrast, for those with low SRS, STwC students (62.0) performed better than the STwM students (56.3). This result also demonstrated that for both groups, students with high SRS have a better understanding of stereochemistry than those with low SRS. The result indicates that students' SRS affects their understanding of stereochemistry with a positive correlation. The Rank-Spearman Correlation test also confirmed this finding, showing a moderate correlation between these two variables ($r_s = 0.383$; $p = 0.004$). The obvious relationship between the two variables proves that the ability to think scientifically affects students' success in understanding stereochemistry.

Figure 9

Example of the question for STSA



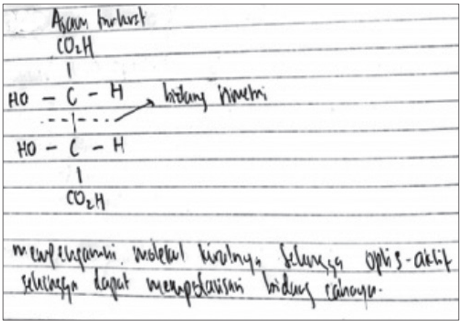
Below are deoxyribose and tartaric acid in Fischer projection

a. How many carbon chiral at the deoxyribose compound and mark those chiral carbon?
b. How many stereoisomer at the deoxyribose compound?
c. Tartaric acid contains 2 carbon chiral but only 3 stereoisomers. Explain why.
d. Which one has the internal plane symmetry between the two? Show it in a figure.
e. What is the effect of internal plane symmetry to its optical activity?

Students with low SRS failed to deal with questions that require thinking at the formal level. Below is an example of those students' errors in explaining why a compound exhibits geometric isomerism and how the plane symmetry in a molecule with chiral carbon atoms affects its optical activity.

Figure 10

Example of students' difficulty in answering the question regarding molecules having internal-symmetry-plane



Asam tartarat

CO_2H

HO – C – H bidang simetri

HO – C – H

CO_2H

mempengaruhi molekul kiralnya, sehingga optis-aktif sehingga dapat mempolarisasi bidang cahaya.

Figure 10 demonstrates students' inability to answer questions displayed in Figure 9. Some students correctly appointed the plane symmetry of tartaric acid (*asam tartarat* in the Indonesian language) but failed to recognise its effect on its optical activity. They believed that *molecules with a plane of symmetry would remain optically active,* as stated (translated from the Indonesian language) in the figure. This difficulty may also be the result of the possibility that they had trouble recognising the compound's optical activity because the tetravalence of the carbon atom did not line up with the polarity of the carboxyl groups at either end. Thus, the carbon atoms at the chain's centre could likewise be identified as chiral centres. Students with good scientific reasoning skills should explain that the existence of an internal symmetry plane divides a compound in half, with the two halves reflecting each other (mirror image). They then should realise that such a molecule with a plane of symmetry is achiral and optically inactive. Some students also struggled to determine whether the enantiomeric pairs were the same compound. Many students believed that the pairs were the same compound confirming a lack of ability to recognise the differences in the position of a molecule's group in three-dimensional space. Students often lack a clear understanding of the idea of optical activity. In the absence of a convincing classroom demonstration, pupils frequently have no choice but to take it on faith (Pecina et al., 1999). However, current technology could assist students in understanding the optical activity phenomenon.

Schwartz et al. (2011) applied an iPad device with the function of a source of polarised light for observing the optical activity of crystal or solution, including NaCl and $NaClO_3$ crystals and sucrose solution.

The Effect of Hands-on and Multimedia Models on Students' Understanding of Stereochemistry

Table 4 shows the percentage of students from each group giving the correct answer to each of the questions. The table shows that, for six questions (1, 2, 4, 5, 9 and 10), the number of STwM students providing a correct answer is greater than that of STwC students. However, the difference between the two groups is quite small. This suggests that multimedia and hands-on models are equally effective in improving students' understanding of stereochemistry, as confirmed by the small difference in scores between STwM and STwC students. The statistical test confirmed the insignificant difference between the two groups.

Both multimedia and hands-on models facilitate students in understanding stereochemistry. Multimedia helps students build mental visualisations because the features of virtual molecular models, animated videos and games allow them to observe three-dimensional molecular shapes from various points of view, allowing their rotation and other movements (Anggriawan, 2017). The mobile and virtual models effectively closed the gap in understanding of students with different spatial abilities (Fatemah et al., 2020). The result of this study is at odds with the work of Abraham et al. (2010), in which computer modelling was found to be better than the physical ball and stick models in aiding students' understanding of stereochemistry. In agreement with the work of Abraham et al. (2010), the physical model was more effective in facilitating students to apply complex stereochemistry concepts compared to the virtual one (Casselman et al., 2021). This finding also conflicts with a study on students' understanding of symmetry, which showed that virtual models favoured students' understanding over physical ones (Thayban et al., 2021). The study strengthened their review results that the contribution of the virtual model will exceed the physical model's contribution (Thayban et al., 2020).

Table 4

The percentage of STwM and STwC students with the correct answer in responding to SAST (Students' Understanding of Stereochemistry Concepts)

Question	STwM (%)	STwC (%)
1	73	72
2	55	44
3	58	61
4	71	64
5	64	47
6	42	44
7	74	79
8	45	55
9	53	40
10	50	41
Average	**58**	**55**

An interesting phenomenon is observed when the stereochemistry scores are a function of students' SRS (Table 5). For students with high SRS, STwM students demonstrated a higher score. Meanwhile, STwC students with low SRS performed better than STwM students with similar low SRS.

Table 5

Students' grade average on stereochemistry test

	SRS category	The average score of the stereochemistry test
STwM	High	66.7
	Low	49.0
STwC	High	60.0
	Low	54.0

Considering the small sample size in this study, it may sound too ambitious to claim that the multimedia model is more effective for high SRS students while the hands-on model is for low SRS students. However, further studies to explore the findings involve bigger respondents.

Conclusion

This study revealed that the difference in students' understanding between those experiencing multimedia and those with the hands-on model is quite small, as confirmed by the Mann-Whitney test's statistical procedure. The result suggests that employing both multimedia and hands-on models in teaching stereochemistry can be effective, and the specific model chosen should be determined by the teaching environment. The average post-test scores for both groups also imply that the application of the two models did not improve students' understanding to a satisfactory level. We do believe that models are the obvious tool to teach stereochemistry. Therefore, exploring why it does not work optimally in this study should be further investigated. It may be reasonable to provide an additional variable to promote a more effective stereochemistry teaching using multimedia and hands-on models. This study also uncovers that students' scientific reasoning skills influence students' understanding of stereochemistry. Regardless of the model applied, the higher students' scientific reasoning, the better their understanding. Therefore, techniques that enhance students' scientific reasoning skills should be deployed to assist their understanding of stereochemistry and other topics.

Implication for the teaching of stereochemistry

This study, and other previous reports, indicate that both hands-on and virtual models are useful in aiding students' understanding of stereochemistry. However, no specific benefit could be determined from deploying either technique. It is therefore recommended that educators select an appropriate medium dependent upon the characteristics of the students, availability of resources and other considerations. There is limited evidence from this study that students with low scientific reasoning skills may benefit from using hands-on models, as this group of students showed a higher score on the stereochemistry test than the group with the same SRS using virtual models. There appeared to be a slight benefit for students with high SRS in using multimedia models. It may be beneficial to choose the appropriate model type depending on the students' scientific reasoning skills.

Limitations of The Study and Future Research Guidelines

Students' scientific reasoning skills were measured before the stereochemistry exercise but not after. One question arising from this study is exploring how teaching using different model types affects students' scientific reasoning skills. The absence of a comparison group in this study could also hinder the transferability of the result to a wider context. Therefore, a future study employing a comparison group and involving a larger number of respondents is highly recommended, especially to determine the relationship between SRS and the effectiveness of different model types. Other variables, such as visualisation skills, motivation, and interest, are also reasonable to explore further. Other drawbacks of this study are the lack of eye tracking as a useful tool informing students' visual ability (Brumberger, 2021) and the spatial ability test as another important factor related to understanding the 3D orientation of stereochemistry. The unavailability of the eye-tracking tool is the reason for the former drawback. We also decided to skip the spatial test ability to reduce the students' workload participating in this study.

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