3D Molecular Interactive Multimedia for Building Chemistry Students' Spatial Ability

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Abstract—Building students' spatial ability to assist them in understanding molecular geometry requires proper multimedia. This study investigated the effectiveness of 3D molecular interactive multimedia (3D-MIM) in improving chemistry students' spatial ability. Thirty chemistry education students of a public university in East Java, Indonesia, participated in this study. This pre-experimental pretest-posttest design employed a set of spatial ability tests referring to the three main dimensions of spatial abilities (spatial relationship, spatial orientation, spatial visualization) and semi-structured interview. Our finding showed that students' spatial abilities for the three domains after experiencing the 3D-MIM fall in the strong and large effects category. The values of N-gain falling in the moderate category and effect size (*d*) in the high category confirm the effectiveness of the 3D-MIM.

Keywords—spatial ability, 3d interactive multimedia, molecular model

1 Introduction

Molecule structure affects its chemical and physical properties, such as melting point, boiling point, density, and reactivity [1], [2]. The topic covers the direction of bonds in molecules, molecular shapes, VSEPR theory, molecular polarity, and introduction to symmetry. The topic of molecular shape is a prerequisite for studying many advanced materials, including point groups, predicting infrared spectra, describing orbitals used in bonding, predicting optical activity, and interpreting electron spectra [4], [24].

Imagining the spatial arrangement of atoms or groups of atoms in a molecule has been a challenge for students when studying the three aspects of molecular forms. Therefore, a strong understanding of molecular geometry is essential for chemistry students. In fact, molecular geometry has been a difficult topic for chemistry students due to their inability to transfer 2D printed images from chemistry textbooks into a 3D molecular structure [5]. They also demonstrated a lack of ability to integrate chemical definition and rules and low spatial structures awareness [6].

An ability to understand the 3D structure of a molecule and mentally imagine its behaviour is known as spatial ability[15],[16]. Lohman [9] defines spatial ability as generating, storing, and manipulating abstract visual images. Spatial abilities require the ability to code, remember, convert, and match spatial stimuli. This ability covers three main domains, including (i) spatial relationship, (ii) spatial orientation, and (iii) spatial visualization. The spatial relationship includes tasks requiring mental rotation of an object either on the (2-D) plane or outside the (3-D) plane. Spatial orientation represents the ability to imagine how an object will look from a different perspective and orientation.

Logic and creative thinking in processing images are needed to solve problems, create new ideas, and improve students' spatial abilities. Spatial abilities are needed in chemistry concepts, such as molecular polarity, molecular geometry, and isomerism. Several studies ([21]–[23]) in general chemistry found that students with high spatial ability performed better in molecular geometry and crystal structure than those with low spatial abilities. It also plays an important role in success in many occupations. However, chemistry educators often fail to develop students' spatial abilities [8].

Proper Media is highly needed in teaching molecular shapes to improve students' understanding of the topic and spatial ability. Commonly, the media applied for teaching this topic are ball and stick media and artificial molecular models[13]. However, these media are static, leading to difficulty interpreting the notation representations and the change between representations. 3D molecular shape modelling can assist students in developing their spatial abilities [28]. Another study employing a 3D molecular model improved chemistry students' understanding of symmetry [15]. Modelling in chemistry has been applied in several areas, including chemical bonding, symmetry, stereochemistry, and other topics [16].

This article describes the implementation of online-based learning assisted 3D-MIM software. The software provides an interactive and dynamic feature for students to visualize the 3D molecular structures.

2 Methodology

2.1 Research design & description of the media

This study employed a pre-experimental group pretest-posttest design and involved 31 Chemistry Education students from a public university in East Java Province, Indonesia. Chemistry education students would like to be chemistry teachers. Therefore, they are also named prospective chemistry teachers.

The teaching of molecular geometry was applied for six weeks to the students using the 3D molecular interactive media (3D-MIM) as the learning media. A tutorial was provided before the teaching for 60 minutes, ensuring that students could operate the media properly. The 3D-MIM has been validated before applying to the teaching and is provided in a mobile format compatible with PC (personal computers), laptops, and smartphones. The Media is presented in the Indonesian language for avoiding language barriers. The example display of the Media is presented in Figure 1. The figure depicts the screenshot of 3D-MIM presenting the molecular geometry of Phosphorus pentachloride (PCl_5). The figure is interactive and can be rotated from every angle allowing students to find out the shape of PCl_5 from a different perspective.

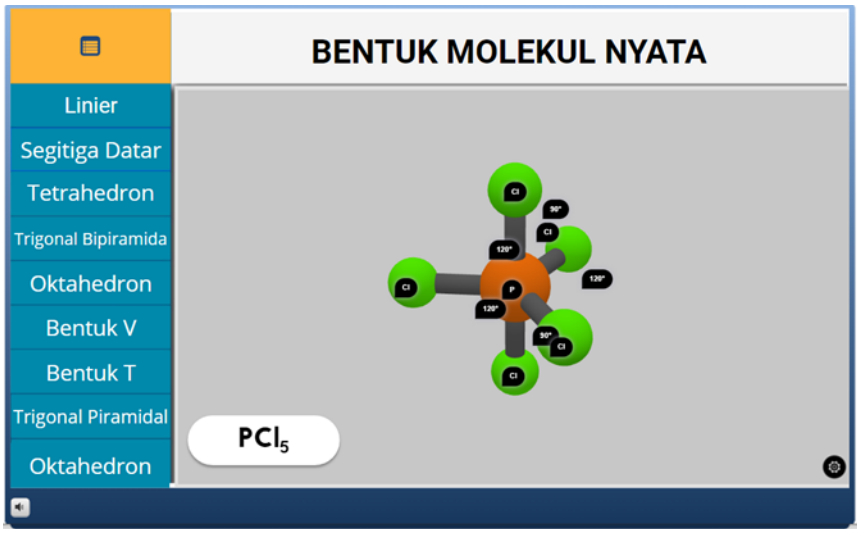

Fig. 1. The example of the 3D-MIM screenshot

The translation of the Indonesian phrases from Figure 1 is as follows. Bentuk molekul nyata is the actual molecular geometry, segitiga datar is trigonal planar, Trigonal Bipiramida is trigonal bypiramidal, Bentuk V is V shape, bentuk T is T shape, trigonal pyramidal is trigonal pyramidal.

2.2 Data collection

Pretest and post-test were applied before and after the molecular geometry teaching assisted 3D-MIM to measure the improvement of students' spatial ability. The instrument for measuring students' spatial ability was 18 multiple-choice questions with free responses on molecular geometry. The instrument was also valid and reliable, with the Cronbach Alpha reliability index of 0.686 falling into the acceptable category. The instrument is available on request.

Semi-structured interviews were also applied to obtain a clear understanding of students' ideas. 10 selected students followed the Interviews for 15 minutes. The results of the post-test, activity observation and reflective journal analysis were the basis for inviting students to attend the interview section.

The writing-drawing technique was used to obtain visual data about students' ability to reflect, rotate, and determine the shape of molecules in various positions. Students were asked to visually describe the observed molecules' reflection, rotation, and shape determination at various positions during the interview process using the writing-drawing technique. Here is the example of the question in the interview: "What would a PCl_5 molecule look like if it is reflected in the XY plane, YZ plane, and XZ plane?"

2.3 Grading scheme and data analysis

The formula and criteria from Hake [30] and a statistical procedure were employed for data analysis. Students' responses were graded according to the following procedures. Score 1 was assigned for the correct option without providing a scientific reason and 2 for a correct answer with a scientific reason.

The improvement of students' spatial ability after the molecular geometry teaching assisted 3D-MIM is interpreted with the normalized gain, <g>, calculated by the Hake [17], [18] formula. The N-Gain Score is interpreted according to Table 1.

Table 1. Interpretation of N-Gain score

N-Gain Score (g)	Category
$g \geq 0,7$	High
$0,7 > g \geq 0,3$	moderate
$g < 0,3$	Low

The effectiveness of the Media is also measured by Effect Size (*d*) according to the following formula:

$$Effect\ size = \frac{Mean\ Posttest - Mean\ Pretest}{Standard\ Deviation} \quad (1)$$

The value of the impact coefficient (and) is interpreted using Cohen's criteria in Coe [19] as presented in Table 2.

Table 2. Interpretation of size effect

Effect size	category
0 – 0,20	small Effect
0,21 – 0,50	medium Effect
0,51 – 1,00	Large Effect
>1,00	Strong Effect

Source: Becker [20]

3 Results and discussion

3.1 Effectiveness of the 3D-MIM in improving spatial ability

The effectiveness of 3d-MIM in improving students' spatial ability was measured based on the Score of pretest and post-test. The average Score of students' pretests was 33.64 (out of 100), while the post-test was 72.40. the increase in spatial ability score between pretest and post-test suggests that the 3D-MIM effectively improves students' spatial ability. The N-Gain Score of 0.63 confirms the improvement was falling in the medium/moderate category. In detail, the improvement of students' spatial ability for each type is presented in Table 3.

Table 3. Description of students' spatial ability for each type

Indicator	Spatial Type	Pretest	Posttest	N-Gain	Category
Determining the number of symmetries	visualization	33,43	72,89	0,59	moderate
Determining molecular geometry	visualization	25.81	67.74	0.57	moderate
Determining the rotation of a compound about the X-axis or Y-axis	Rotation	39,52	72,58	0,55	moderate
Transferring 2D molecular representation to 3D, and vice versa	Relation	32.37	72.58	0.59	moderate

Table 3 shows that each type of spatial ability (visualization, rotation, and relation) demonstrates similar N-gain values falling in moderate categories. These values imply that students' spatial ability in all three domains improved significantly after the teaching assisted 3D-MIM.

The improvement of students' spatial ability is also confirmed by the effect size values (*d*) displayed in Table 4. For the visualization types, the one measured based on students' responses to symmetry was in a strong category, while molecular geometry was a large category. The rotation and relation types fall in the large and strong categories, respectively.

Table 4. Size effect of each type of visual-spatial

Spatial Type	N	Pretest		Post-test		*d*	Category
		Mean	***SD***	***mean***	***SD***		
visualization	31	33.42	17.06	72.89	36.74	1.37	Strong Effect
visualization	31	25.80	44.48	67.74	47.51	0.911	Large effect
Rotation	31	39.51	30.12	72.58	38.38	0.95	Large effect
relation	31	32.36	22.67	72.58	40.49	1.22	Strong Effect

The magnitude of the effect size on the three types of spatial ability (spatial relationships, spatial orientation, and spatial visualization), according to Cohen [21], is classified as large. Again, the values indicate that the teaching of molecular geometry assisted 3D-MIM effectively increases the three dimensions of spatial ability.

The interactive feature of the 3D-MIM may contribute to the improvement of students' spatial ability. Students can rotate them dynamically and interactively. They actively observe changes in the position of atoms and compare the arrangement of atoms clearly in the intermediate space before and after rotation. Students' visuospatial sketches and visual stimulation activate the working memory component through this process. Thus, the dimensions of the spatial relationship involving the rotation operation are improved. As shown in Figure 2, students can experience a proper way of rotating the 3D molecular structure. The structure can be rotated to and from any direction (360°).

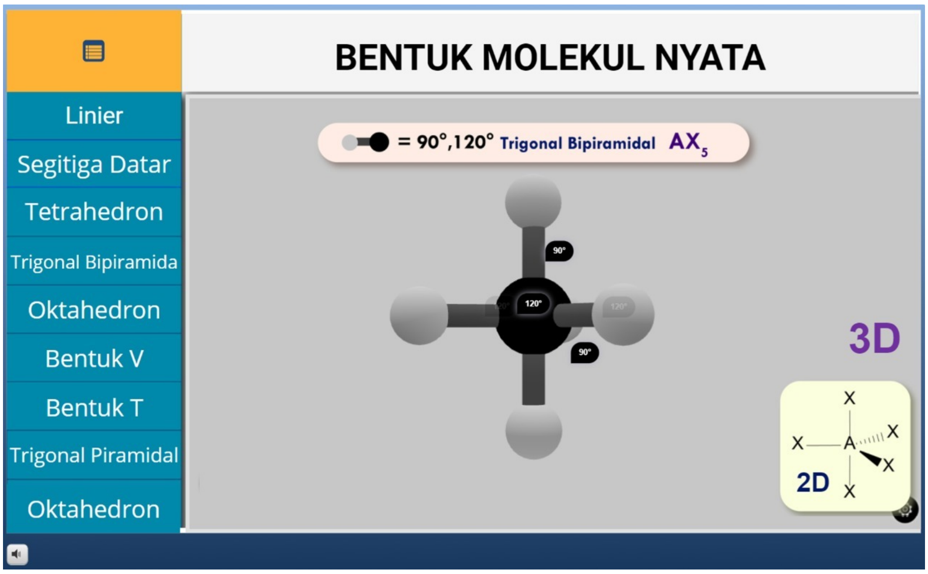

Fig. 2. The preview of 3D molecular geometries models that can rotate until 360◦[22]

The 3D-MIM visualization also ignites the active site of the visuospatial sketch path, the part of the brain responsible for storing visual and spatial information in working memory. Cognitive psychology supports this cognitive process that visual stimuli will activate a component of working memory, visuospatial sketching. Visual information that enters working memory will be selected. Meaningful information will be encoded as part of the knowledge system stored in long-term memory.

Tasker [23] stated that visualization of molecules through computers helps convey information to gain new knowledge. Abraham et al. [5] reported that the group of students teaching stereochemistry who were given a computerized representation of molecules scored significantly higher than those given ball and stick physical models and 2D images.

Precise manipulations carried out by the lecturer for two consecutive semesters in Inorganic Chemistry succeeded in significantly increasing post-test scores on topics of bond angles and 3D molecular properties such as chirality and conformation. In addition, learning with visualization media is interesting and helps students understand abstract molecules. In other studies, the inquiry training learning model assisted by visual media provided an entertaining learning environment and helped students understand abstract concepts [24].

3.2 Interview

To ensure the improvement of students' spatial ability, we invited ten selected students to attend the subsequent interview. Some interview results are presented as follows. Student 1 admitted that:

" . . . we visualize the shape of the molecule visually in the brain, it's quite difficult. However, by using the 3D-MIM, the molecule's shape can be rotated with your finger and looks like a three-dimensional model."

This transcript confirms that students memorize the shape of the molecule and visualize & observe the orientation of the 3D shape of the molecule.

4 Conclusion

This study revealed that the teaching of molecular geometry assisted 3D-MIM, effectively improving chemistry students' spatial abilities for the three domains (visual, relation, and orientation). The N-gain confirmed the improvement of students' spatial abilities in the moderate category. The effect size of the spatial relation was in a strong category, rotation in a large category, and visualization in both large and strong categories. This study implies that chemistry teaching assisted 3D interactive Media is highly recommended. However, we also uncovered some difficulties encountered by students in the three spatial ability domains.

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