SPATIAL ABILITY: MEASURING ITS CONTRIBUTION TO SYMMETRY UNDERSTANDING

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Abstract – The spatial ability affects the understanding of the material that is a three-dimensional representation. This study aims to calculate the contribution of spatial ability to understanding symmetry. The research method used is correlational quantitative, with Sixty-two Chemistry Department students in the fifth semester taking chemical bonding courses. Tests of spatial intelligence and familiarity with molecular symmetry were used to compile information. The Pearson product-moment test was used to analyse the data. The results showed that students' spatial ability in the high category had a positive relationship with students' success in understanding molecular symmetry.

Keywords: *Spatial Ability, Symmetry, Representational Competence.*

INTRODUCTION

Molecular symmetry covers the concept of symmetry operations of a molecule that students need to understand because it is a prerequisite in understanding advanced chemistry. The topic is used to understand solid-state chemistry, crystallography, stereochemistry, and quantum chemistry. (Achuthan et al., 2018; Antonoglou et al., 2011; Cass et al., 2005; Fuchigami et al., 2016; Kang & Kim, 2021; Niece, 2019; Schiltz & Oliver-Hoyo, 2012; Thayban et al., 2020, 2021). By knowing the symmetry operation, the polarity and chirality of a molecule can be predicted. In addition, molecular symmetry can be attributed to the polarity and scalability of the molecule (Atkins & de Paula, 2006; Effendy, 2017).

Molecular symmetry consists of two concepts: symmetry operations and symmetry elements. Symmetry operations are rearrangements of atoms in a molecule based on rotation about the true axis, the reflection of the mirror plane, inversion through the centre, and rotation of the apparent axis. Symmetry elements can be lines, planes or points. Lines are symmetry elements for rotations about the true axis, planes are symmetry elements for reflections on the mirror plane, and points are symmetry elements for operations at the symmetry centre (Atkins & de Paula, 2006; Effendy, 2017; Thayban et al., 2020).

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Efforts in understanding molecular symmetry operations, such as identifying true rotation axes, mirror plane reflections, and rotations through pseudo rotation axes, must perform several cognitive tasks. First, build a good representation or visualisation of three-dimensional objects in space (Harle & Towns, 2011). Second, manipulating representations of three-dimensional objects in space (Tuvi-Arad & Gorsky, 2007). These tasks can be done correctly if students have good spatial visualisation, spatial orientation, and spatial relations skills (Achuthan et al., 2018; Al-Balushi & Al-Hajri, 2014; Kang & Kim, 2021; Thayban et al., 2021; Tuvi-Arad & Gorsky, 2007). Spatial visualisation is the ability that allows one to correctly interpret a two-dimensional representation of a three-dimensional object's shape and orientation. In addition, students must imagine molecular shapes' appearance from various points of view (Al-Balushi & Al-Hajri, 2014; Tuvi-Arad & Gorsky, 2007). This cognitive process can be done well by students if students have high spatial orientation. Spatial orientation is the ability to determine how an object looks when viewed from a different perspective. In addition, students must also have high spatial relations skills. Spatial relations are the ability to imagine the movement of two-dimensional or three-dimensional objects (Lohman et al., 1979).

The ability of spatial visualisation, spatial relations, and spatial orientation in a single unit is referred to as spatial ability. Spatial ability can be defined as building mental visualisations or images of three-dimensional objects based on two-dimensional representations and performing rotations or inversions of these mental visualisations (Barnea, 2000a). Recent research reports revealed that students still find it difficult to visualise two-dimensional shapes, which means that students' spatial abilities are very low (Harle & Towns, 2011; Kang & Kim, 2021; Stieff, 2007, 2011; Stieff & Raje, 2010; Thayban et al., 2021; Wu & Shah, 2004). Tuckey & Selvaratnam (1993) stated a cause of the low spatial ability of students is difficulty identifying the position of the axis of rotation relative to objects based on the visualisation of objects before and after rotation. They also had difficulty visualising objects' appearance after rotation and reflection operations. However, research on the effect of spatial ability on chemistry is not mutually reinforcing. Koutalas et al. (2014) showed that spatial ability was not related to the ability to complete the test matching various diagrams of organic molecules because they were familiar with the molecule. On the other hand, Stieff et al. (2012) found a relationship between spatial ability and understanding of stereochemistry.

METODE

The study employed a descriptive and correlational design. The descriptive design describes students' spatial abilities, while correlational research designs examine the relationship between spatial abilities and students' understanding of molecular symmetry. Sixty-two Chemistry Department students in the fifth semester (26 boys, 36 girls) (Age: $M = 20.5$; $SD = 0.74$) take chemical bonding courses. Participants were determined using a convenience sampling technique. All participants were tested for equivalence by providing a molecular shape test. The homogeneity test using Levene's Test ($P > .05$) showed that the molecular shape test scores had the same variance (homogeneous). The average similarity test was performed using a one-way ANOVA ($F (1.61) = 1.446$; $P > .05$) indicates that there is no significant difference in the test scores of the Molecular Forms material. The spatial ability test is carried out for 45 minutes with three stages: doing the PSVT test: Visualisation, PSVT: Rotation, and PSVT with 15 minutes of orientation each.

Research Instrument

Spatial Ability

Students' spatial abilities were evaluated using a 30-item multiple-choice version of the Purdue Spatial Visualization Test (PSVT) created by Guay. For the most part, this tool has been the gold standard for investigating spatial intelligence. Category reliability for the spatial ability exam is 0.95, which is very high.

Students Understanding of Molecular Symmetry Test (SUMST)

The SUMST was a multiple-choice quiz that reflected all of the symmetries found in the molecule. Cronbach's alpha for this 18-item assessment was 0.905, putting it in the high-reliability category. After making a request, you can have access to the instrument.

Data Analysis

Descriptive Analysis

Descriptive quantitative analysis was used to obtain data on the distribution of students based on their spatial abilities. The correct answer was given a score of 1, and the wrong answer was a score of 0. The students' spatial ability level was categorised based on the spatial ability test score. The categorisation is done by adapting the average category of spatial ability test scores. Students with above-average scores are included in the high category of students with spatial abilities. Those who scored below the mean, on the other hand, are considered to have poor spatial abilities.

Correlational Analysis

Correlational analysis was conducted to determine the relationship between spatial ability and students' understanding of molecular symmetry. The normality test and the homogeneity test are necessary precursors to this analysis. The Kolmogorov-Smirnov test (One Sample K-S) normality results obtained P >.05, indicating that the score data follows a normal distribution. Levene's Test indicates that the score data is homogeneous, as the significance level is greater than.05. Correlational analysis was performed using the Pearson product-moment correlation using SPSS.

RESULT AND DISCUSSION

Student Spatial Ability

Students' spatial abilities were measured with the PSVT test: Visualization (V), PSVT: Rotation (R), and PSVT: Orientation (O). Based on three types of spatial questions, Students' spatial abilities were classified into three categories, including spatial visualisation (V), relation (R), and orientation (O) (Barnea, 2000b; Harle & Towns, 2011; Rahmawati et al., 2021; Thayban et al., 2021). The results of students' ability scores in the descriptive analysis are shown in Table 1.

Table 1. Students Spatial Ability

Spatial Ability category	Number of Students	Number of questions	Average Score	Standard Deviation	Percentage of Students (%)	
					Height	Low
PSVT: V		10	5,66	1,525	77,4	22,6%
PSVT: R	62	10	5,21	2,188	58,1	41,9%
PSVT: O		10	6	1,890	75,8	24,2%

This finding is in accordance with previous research (Anggriawan et al., 2017; Budinoff & McMains, 2018; Stieff et al., 2018; Thayban et al., 2021). The results revealed students' spatial abilities had a high spatial ability. It is also known that some students still had low spatial abilities. Students' spatial ability is included in the high category. Thus, it can be considered that students have developed spatial abilities well as partial abilities are developing thinking skills that have reached the final stage of formal thinking (Inhelder & Piaget, 1958) and experience in studying three-dimensional objects with good quantity and quality (Barke & Engida, 2001; Tuckey & Selvaratnam, 1993). Furthermore, students with low spatial abilities were 49%. It can be considered that the student has not developed spatial abilities well. This finding follows research Anggriawan et al., (2017) found 40% of students with low spatial ability, and Koutalas et al., (2014) found that students have the spatial ability with an average of 56% (low category).

Students with low spatial abilities do not follow the research results Barke & Engida, (2001) that spatial abilities develop well at 11-16 years old. At this age, one has reached the final formal thinking ability (Inhelder & Piaget, 1958), which means that they have been able to think abstractly. Thus, it can be said that students with an average age of 20-21 should have developed spatial abilities well. Several things may cause this. First, the students' thinking level has not yet reached their formal thinking ability. Spatial thinking, such as visualising, rotating, and looking at objects from different perspectives, requires abstract thinking skills. This assumption is supported by research Rakhmawan & Vitasari, (2016) that there are chemistry students with concrete-transition thinking skills, as much as 37.5%. As a result, students with this thinking ability have difficulty constructing, manipulating, and visualising an object's movement, so they cannot do the tasks in the spatial ability test well (Barke & Engida, 2001).

Second, the students' spatial working memory capacity is very small. The capacity of spatial working memory is small due to the observation of objects not accompanied by interpreting and visualising the movement of objects so that the existing visual information cannot be processed properly (Salthouse, 1990). As a result, students easily experience cognitive overload when thinking spatially. Thus, students who experience cognitive overload have difficulty in doing spatial ability tests (Mayer, 2009; Tversky, 2005)

Third, the learning experience in the form of a three-dimensional object is not accompanied by a deep meaning for the visualisation of the object. Students majoring in chemistry have many learning experiences related to three-dimensional objects. For example, they were studying the material of molecular shape and stereochemistry. The material requires students to correctly imagine and visualise two-dimensional shapes into three dimensions to understand the studied object. Thus, the learning experience should support the development of students' spatial thinking skills (Barke & Engida, 2001; Tuckey & Selvaratnam, 1993). However, based on the findings of this study, it can be indicated that students studying the material do not understand the three-dimensional shape and movement of objects. As a result, students cannot do spatial ability test tasks.

Fourth, the lack of work on three-dimensional form problems with a high level of complexity (Pribyl & Bodner, 1987). The undeveloped spatial ability of students is caused by students not being used to working on problems with complex three-dimensional objects. For example, based on the observations made in this study, students can only work on molecular shape problems with coordination numbers from 2 to 4. They also have difficulty doing spatial ability test tasks with a high level of complexity, such as visualisation and rotation.

Relationship between Spatial Ability and Understanding of Molecular Symmetry

Student responses to the SUMST apparatus are shown in Table 2, reflecting their understanding of molecular symmetry at high and low spatial ability.

Table 2. Students' Responses to the SUMST and spatial ability level

Spatial Ability	Student's Symmetry Square
Height	X = 59,05 N = 36 SD = 16,38
Low	X = 40,57 N = 26 SD = 21,27

The results of the Person Product-moment correlation test to determine the relationship between spatial ability and understanding of student molecular symmetry using the SPSS Statistic application obtained $r(62) = +0.395$; $P < .05$. Spatial ability affects students' success in understanding symmetry material. Spatial ability positively relates to students' success in understanding molecular symmetry. This shows that students with high spatial abilities better understand molecular symmetry than those with low spatial abilities. This finding is supported by research Achuthan et al., (2018) and Tuvi-Arad & Blonder, (2010) that students with high visual-spatial thinking skills successfully understand molecular symmetry. On the other hand, students with low spatial ability have difficulty understanding molecular symmetry. Students' spatial ability contributes 15,60% to success in understanding molecular symmetry. The relationship is included in the sufficient category.

Students with high spatial abilities can use spatial visualisation skills, spatial orientation skills, and spatial relations skills well to provide convenience in understanding molecular symmetry, such as rotation, reflection, inversion, and pseudo-rotation operations. The effect of students' spatial ability on success in understanding molecular symmetry can be explained as follows. First the ability of spatial visualisation. Based on this ability, students are expected to be able to build representations or visualisations of three-dimensional objects in space with good quality (Harle & Towns, 2011) so that students more easily understand the operation of symmetry. For example, the determination of the reflection operation on the AsH_3 molecule. Students with low spatial ability showed that the AsH_3 molecule has four mirror planes, one horizontal mirror plane and three dihedral mirror planes (Figure 1).

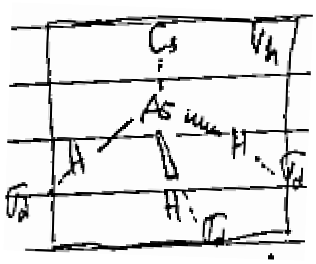

Figure 1. Representation of Students with Low Spatial Ability Shows Mirror Plane on AsH_3 Molecule

Figure 1 revealed students with low spatial abilities are thought to be low in spatial visualisation skills, which causes they cannot translate the full notation visual code ( ) and broken bond notation (··········) in the molecular structure (Wu & Shah, 2004). As a result, students are wrong in constructing the representation of the shape of the AsH_3 molecule in space.

Second, the ability of spatial relations. Based on this ability, students are expected to be able to manipulate representative three-dimensional objects in space (Tuvi-Arad & Gorsky, 2007) so that it is easier for students to understand molecular symmetry. For example, determine the rotation operation of the SO_2F_2 molecule. Students with low spatial ability showed that the SO_2F_2 molecule has a C3 rotation operation (Figure. 2).

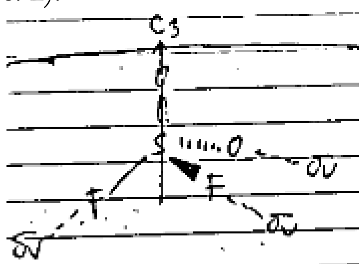

Figure 2. Representation of Students with Low Spatial Ability Shows Rotation Operations on SO_2F_2 Molecule.

Figure 2 shows students with low spatial abilities are thought to be caused by the inability to determine the molecular shape equivalent to the initial molecular shape after being subjected to rotation operations. Based on this, it can be said that the student cannot use spatial relation skills.

As a result, students make mistakes in representing three-dimensional objects before and after being subjected to rotation operations.

Third, the ability of spatial orientation. Based on this ability, students are expected to determine a molecular object's appearance when viewed from a different perspective (Lohman et al., 1979) so that it can show the rotational operation of the molecule on different axes. For example, the determination of the rotation operation on the SeF_6 molecule. Students with low spatial ability showed that the SeF_6 molecule only has a rotational operation of C4 as the main axis (Figure. 3).

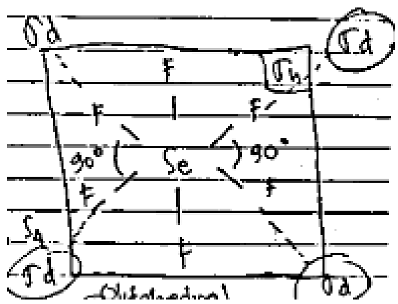

Figure 3. Representation Students with low spatial ability show rotational operations on the SF_6 molecule

Figure 3 shows that low-ability students are thought to be caused by the inability to imagine the appearance of the SeF_6 molecule from various points of view until a new perspective is obtained, which allows determining the existence of other rotational operations. Thus, the student is not able to use the ability of spatial orientation, causing failure in determining the rotation operation on the SeF_6

Fourth, students can combine spatial visualisation skills, spatial orientation, and spatial relations. With the combination of these three abilities, students are expected to be able to represent and manipulate objects from various points of view with good quality. For example, the determination of the rotation operation through the pseudo axis (Sn) in the CCl_4 molecule. Students with low spatial ability could not show any pseudo-axis rotation operation on the CCl4 molecule (Figure. 4).

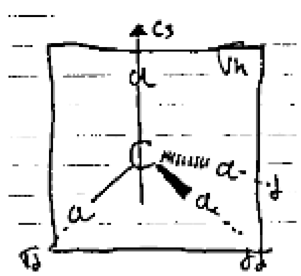

Figure 4. Representation of Students with Low Spatial Ability Shows Rotation Operations through the Pseudo Rotation Axis on CCl_4 Molecules

Two mistakes in Figure 4 are blamed for this discrepancy. The first problem is that while students can correctly complete rotational operations, they often struggle with reflectional ones. The second mistake is that the student understands how to perform rotation and reflection operations correctly but cannot figure out where the new molecule should be located from an entirely new perspective. Students' spatial abilities are average because some can only use spatial relations skills but not spatial visualisation abilities. They can also use spatial relations skills and spatial visualisation abilities but cannot use spatial orientation skills.

CONCLUSION

Spatial ability positively relates to students' success in understanding molecular symmetry. The students' spatial ability is included in the high category. This shows that students with high spatial abilities better understand molecular symmetry than those with low spatial abilities.

REFERENCES

Achuthan, K., Kolil, V. K., & Diwakar, S. (2018). Using virtual laboratories in chemistry classrooms as interactive tools towards modifying alternate conceptions in molecular symmetry. *Education and Information Technologies*. https://doi.org/10.1007/s10639-018-9727-1

Al-Balushi, S. M., & Al-Hajri, S. H. (2014). Associating animations with concrete models to enhance students' comprehension of different visual representations in organic chemistry. *Chemistry Education Research and Practice*. https://doi.org/10.1039/c3rp00074e

Anggriawan, B., Effendy, & Budiasih, E. (2017). Kemampuan Spasial Dan Kaitannya Dengan Pemahaman Mahasiswa Terhadap Materi Simetri. *Jurnal Pendidikan*. 2(12), 1612-1619

Antonoglou, L. D., Charistos, N. D., & Sigalas, M. P. (2011). Design, development and Implementation of a technology enhanced hybrid course on molecular symmetry: Students' outcomes and attitudes. *Chemistry Education Research and Practice*. https://doi.org/10.1039/C0RP90013C

Atkins, P., & de Paula, J. (2006). Physical Chemistry 8th Edition. In *W.H. Freeman and Company New York*.

Barke, H.-D., & Engida, T. (2001). Structural Chemistry and Spatial Ability In Different Cultures. *Chemistry Education Research and Practice*, *2*(3), 227–239. https://doi.org/10.1039/B1RP90025K

Barnea, N. (2000b). Teaching and Learning about Chemistry and Modelling with a Computer managed Modelling System. In J. K. Gilbert & C. J. Boulter (Eds.), *Developing Models in Science Education* (pp. 307–323). Springer Netherlands. https://doi.org/10.1007/978-94-010-0876-1_16

Budinoff, H., & McMains, S. (2018). Relationships between Spatial Visualization Ability and Student Outcomes in a 3D Modeling Course. *Engineering Design Graphics Journal*.

Cass, M. E., Rzepa, H. S., Rzepa, D. R., & Williams, C. K. (2005). An Animated Interactive Overview of Molecular Symmetry. *Journal of Chemical Education*, *82*(11), 1742. https://doi.org/10.1021/ed082p1742

Effendy. (2017). *Molekul, Struktur, dan Sifat-sifatnya*. Indonesian Academic Publishing.

Fuchigami, K., Schrandt, M., & Miessler, G. L. (2016). Discovering Symmetry in Everyday Environments: A Creative Approach to Teaching Symmetry and Point Groups. *Journal of Chemical Education*. https://doi.org/10.1021/acs.jchemed.5b00325

Harle, M., & Towns, M. (2011). A review of spatial ability literature, its connection to chemistry, and implications for instruction. In *Journal of Chemical Education*. https://doi.org/10.1021/ed900003n

Inhelder, B., & Piaget, J. (1958). The growth of logical thinking: From childhood to adolescence. In A. Parsons & S. Milgram (Eds.), *The growth of logical thinking: From childhood to adolescence*. Basic Books. https://doi.org/10.1037/10034-000

Kang, M., & Kim, J. (2021). A Study on the ZnO Thin Film Deposited by RF Sputtering Method as an Electron Transport Layer in Quantum Dot Light-Emitting Diodes. *Korean Journal of Metals and Materials*, *59*(10), 718–723. https://doi.org/10.3365/KJMM.2021.59.10.730

Koutalas, V. G., Antonoglou, L. D., Charistos, N. D., & Sigalas, M. P. (2014). Investigation of Students' Ability to Transform and Translate 2D Molecular Diagrammatic Representations and its Relationship to Spatial Ability and Prior Chemistry Knowledge. *Procedia - Social and Behavioral Sciences*, *152*, 698–703. https://doi.org/https://doi.org/10.1016/j.sbspro.2014.09.265

Lohman, D. F., States., U., Office of Naval Research, University., S., & School of Education. (1979). *Spatial ability: a review and reanalysis of the correlational literature*. https://htext.stanford.edu/dd-ill/spatial-ability.pdf

Mayer, R. E. (2009). *Multimedia Learning* (2nd ed.). Cambridge University Press. https://doi.org/DOI: 10.1017/CBO9780511811678

Niece, B. K. (2019). Custom-Printed 3D Models for Teaching Molecular Symmetry. *Journal of Chemical Education*, *96*(9), 2059–2062. https://doi.org/10.1021/acs.jchemed.9b00053

Pribyl, J. R., & Bodner, G. M. (1987). Spatial ability and its role in organic chemistry: A study of four organic courses. *Journal of Research in Science Teaching*. https://doi.org/10.1002/tea.3660240304

Rahmawati, Y., Dianhar, H., & Arifin, F. (2021). Analysing students' spatial abilities in chemistry learning using 3d virtual representation. *Education Sciences*, *11*(4). https://doi.org/10.3390/educsci11040185

Rakhmawan, A., & Vitasari, dan M. (2016). Kemampuan berpikir logis sebagai prediktor keberhasilan mahasiswa dalam perkuliahan kimia dasar. *Jurnal Penelitian Dan Pembelajaran IPA*, *2*, 99–109.

Schiltz, H. K., & Oliver-Hoyo, M. T. (2012). Physical models that provide guidance in visualisation deconstruction in an inorganic context. *Journal of Chemical Education*. https://doi.org/10.1021/ed200540p

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction*. https://doi.org/10.1016/j.learninstruc.2007.01.012

Stieff, M. (2011). When is a molecule three dimensional? A task-specific role for imagistic reasoning in advanced chemistry. *Science Education*. https://doi.org/10.1002/sce.20427

Stieff, M., Origenes, A., DeSutter, D., Lira, M., Banevicius, L., Tabang, D., & Cabel, G. (2018). Operational constraints on the mental rotation of STEM representations. *Journal of Educational Psychology*. https://doi.org/10.1037/edu0000258

Stieff, M., & Raje, S. (2010). Expert algorithmic and imagistic problem-solving strategies in advanced chemistry. *Spatial Cognition and Computation*. https://doi.org/10.1080/13875860903453332

Stieff, M., Ryu, M., Dixon, B., & Hegarty, M. (2012). The role of spatial ability and strategy preference for spatial problem solving in organic chemistry. *Journal of Chemical Education*. https://doi.org/10.1021/ed200071d

Thayban, T., Habiddin, H., & Utomo, Y. (2020). Concrete Model VS Virtual Model: Roles and Implications in Chemistry Learning. *J-PEK (Jurnal Pembelajaran Kimia)*, *5*(2), 90–107. https://doi.org/10.17977/um026v5i22020p090

Thayban, T., Habiddin, H., Utomo, Y., & Muarifin, M. (2021). Understanding of Symmetry: Measuring the Contribution of Virtual and Concrete Models for Students with Different Spatial Abilities. *Acta Chimica Slovenica*, *68*(3), 736–743. https://doi.org/10.17344/acsi.2021.6836

Tuckey, H., & Selvaratnam, M. (1993). Studies Involving Three-Dimensional Visualisation Skills in Chemistry: A Review. *Studies in Science Education*, *21*(1), 99–121. https://doi.org/10.1080/03057269308560015

Tuvi-Arad, I., & Blonder, R. (2010). Continuous symmetry and chemistry teachers: Learning advanced chemistry content through novel visualisation tools. *Chemistry Education Research and Practice*. https://doi.org/10.1039/c001046b

Tuvi-Arad, I., & Gorsky, P. (2007). New visualisation tools for learning molecular symmetry: A preliminary evaluation. *Chemistry Education Research and Practice*. https://doi.org/10.1039/B6RP90020H

Tversky, B. (2005). *Visualspatial reasoning* (In K. J. Holyoak & R. Morrison, Ed.). Cambridge University Press.

Wu, H. K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. In *Science Education*. https://doi.org/10.1002/sce.10126