JTK: Jurnal Tadris Kimiya 8, 1 (June 2023): 1-9
Website: http://journal.uinsgd.ac.id/index.php/tadris-kimiya/index
ISSN 2527-9637 **(online) ISSN** 2527-6816 **(print)**

Chemistry Students' Understanding of Lewis Structure, VSEPR Theory, Molecular Geometry, and Symmetry: A Cross-Sectional Study

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Received: 7 March 2023; Accepted: 25 May 2023; Published: 30 June 2023

Abstract

Most chemical concepts are abstract, hierarchical, and constructed from basic to complex concepts. Lewis structure, VSEPR theory, molecular geometry, and molecular symmetry have hierarchical idea. This study attempted to characterise and determine the relationship between students' knowledge of Lewis structure, VSEPR theory, molecular geometry, and molecular symmetry of the 1st, 2nd, and 3rd-year chemistry students at a public university. This study involved 88 students in total selected using proportionate stratified random sampling. The instrument was a relevant short-answer question on the three topics. The data were measured using nonparametric statistics, especially the Kruskal-Wallis difference and Spearman Rank correlation tests. This study's results show differences in understanding of Lewis structure, molecular geometry, and symmetry between the 1st, 2nd, and 3rd-years students. The 3rd-year students always performed better than the 1st and 2nd-year students for all topics. The test result confirms a positive and strong relationship between students' understanding of Lewis structure and molecular geometry for the three groups of students with ρ values of 0.979, 0.979, and 0.966 (< 0.01) for 1st, 2nd, and 3rd-year students, respectively.

Keywords: chemistry students, cross-sectional study, understanding chemical concepts

DOI : https://doi.org/10.15575/jtk.v8i1.24410

1. Introduction

Chemistry studies the properties, structures, changes, and energies associated with it. Most chemical concepts are abstract, and hierarchies from simple to advanced ones. Lewis structure, molecular geometry, and symmetry are examples. Knowledge of Lewis structure is required to determine a molecule's geometry correctly. Also, the geometry of molecule comprehension is a valuable asset for mastering molecular symmetry. Students starting chemistry lessons often struggle to understand even the most basic Lewis dot structures (Nassiff & Czerwinski, 2015). Getting good at building and manipulating Lewis structures and Valence Shell Electron Pair Repulsion (VSEPR) theory is a crucial first step on the road to representational competence. Lewis structures provide a helpful framework for students to build upon their existing chemistry knowledge and use it to predict a wide range of physical and chemical properties (Tiettmeyer et al., 2017).

In Indonesia, Lewis structure and molecular geometry are covered in the secondary school curriculum, while symmetry is introduced at the university level. Chemistry students study molecular geometry at several Indonesian universities in the 1st-year in Basic Chemistry and Chemical Bond Structure. Meanwhile, molecular symmetry is explored at some universities in the 2nd-year of the Physical Inorganic Chemistry course.

The ability to recognise symmetry patterns in molecules is crucial for success in chemistry (Crandell & Pazicni, 2023), including the calculation of lattice energy (Miras et al., 2022), crystallography (Duda et al., 2020), bonding and spectroscopic transitions (Achuthan et al., 2018) and other applications (Dias & Faria, 2020). Undergraduate chemistry courses typically include instruction on recognising intramolecular symmetries due to the widespread importance of molecular symmetry. However, intermolecular symmetry, or symmetry between groups of molecules, is critically important in fields like X-ray crystallography, yet it is rarely discussed (Ruiz & Johnstone, 2020). Finding symmetry elements and the corresponding symmetry operations requires mental manipulation of molecules (Rattanapirun & Laosinchai, 2021). Insufficient knowledge of Lewis structure and VSEPR will likely lead to a misunderstanding of molecular geometry, while an unscientific understanding of molecular geometry will lead to difficulty and erroneous ideas in symmetry. A study by Thayban et al. (2021) found that students tend to describe the shape of molecules only based on Lewis structure without considering the molecule's position as a three-dimensional object.

Some terminologies stating a person's correct and incorrect understanding of a particular concept or scientific and chemical phenomena are used interchangeably in this paper. The terms for correct understanding include scientific understanding, strong knowledge, robust knowledge, robust understanding, and deep understanding. Meanwhile, unscientific understanding, incorrect ideas, erroneous ideas, alternative conceptions, misconceptions, and misunderstanding are applied to incorrect ones. We have described these terminologies in previous works (Habiddin & Nofinadya, 2021; Habiddin & Page, 2019).

Third-year university students should likely better understand the three topics because they have more exposure to the topics. It has been found that the amount of time a student spends in school affects the methods they employ to hone their oral communication skills (Dinsa et al., 2022).

2. Research Method

This descriptive study employed a cross-sectional design with a correlational approach. The study involved three groups of students (88 in total), including the 1st, 2nd, and 3rd-year Bachelor of Chemistry Education students attending the 2021/2022 academic year. Seven hundred one chemistry students in the population with the composition 284 from 1st-year (class of 2021), 230 from 2nd-year (class of 2020), and 187 from 3rd-year (class of 2019) were selected using a proportionate stratified random sampling method. Using the Slovin formula with a confidence level of 90%, we obtained 23, 29, and 36 students from 1st, 2nd, and 3rd-year students, respectively, for participating in this study.

Table 1 depicts the course the respondents experienced that discuss Lewis structure, molecular geometry and symmetry.

Table 1. Course Taken by the Three Groups

Topic	1st-year	2nd-year	3rd-year
	Course coverage		
Lewis Structure	Basic chemistry, Structure & chemical bonding	Basic chemistry, Structure & chemical bonding	Basic chemistry, Structure & chemical bonding
Molecular Geometry	Basic chemistry, Structure & chemical bonding	Basic chemistry, Structure & chemical bonding	Basic chemistry, Structure & chemical bonding
Symmetry	Structure & chemical bonding	Structure & chemical bonding	Structure & chemical bonding, solid state chemistry

This research instrument consists of fifteen questions with five relevant questions for each topic. The instrument was validated by a Chemistry staff. The validator's feedback was considered for revising the instrument before data collection. Here are the examples of three relevant questions:

SO_2F_2 is a colorless inorganic gas compound. (a) draw the Lewis structure of SO_2F_2, (b) determine the molecular geometry of the molecules, (c) show the symmetry elements of the molecules.

3. Result and Discussion

3.1. Students' Understanding of Lewis Structure

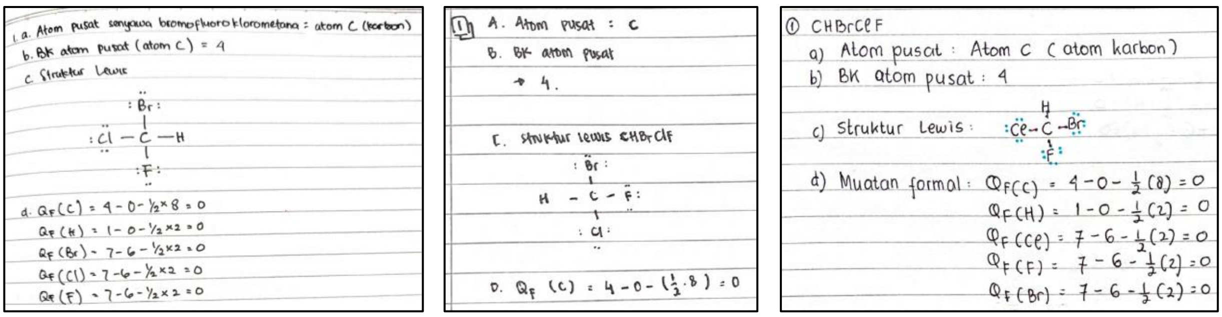
The comparison of the students understanding between the three groups on Lewis structure is depicted in Table 2. The table shows that 3rd-year students exhibit the highest-grade average on Lewis structure with 96.80, while the 2nd-year is the lowest with 85.56. Surprisingly, the average score of 1st-year students passes the average of 2nd-year ones.

Table 2. Comparison of Students' Understanding of Lewis Structure

	N	Lowest score	Highest score	Average score	Standard Deviation
1st-year	36	43.33	100	85.56	14.16
2nd-year	29	53.33	100	75.30	14.96
3rd-year	23	83.33	100	96.80	4.43

However, in Table 1, it is clear that the learning experience toward the Lewis structure topic between the two groups (1st and 2nd-years) was similar. This result implies the advantage of university experience of the 2nd-year students over the 1st-year students do not contribute significantly to their understanding of the topics. Meanwhile, the lowest score was demonstrated by the 1st-year students with 43.33, and the 3rd-year students were the best of the three groups.

For the highest score, some students from the three groups reached a peak score of 100. Regarding the differences, the three groups also demonstrated similar answers to some questions, as observed in Figure 1. When answering the question regarding the coordination number, formal charge, and Lewis structure of CHBrClF, the three groups of students produced an equal answer level. The standard deviation of the 3rd-year student is the lowest, meaning that score for each student clustered around 96.80. Meanwhile, the scores for 1st and 2nd-year students are more spread out.



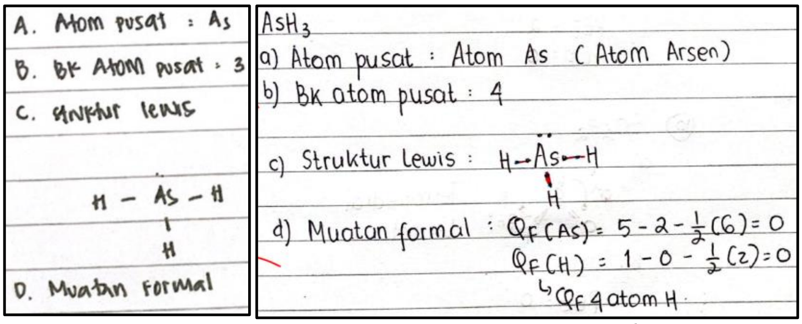
(a) (b) (c)

Figure 1. Students' Answers to a Lewis Structure Question: (a) 1st, (b) 2nd, (c) 3rd Years
(a. Central atom of CHBrClF; b. Coordination number of the central atom; c. Lewis structure; d. Formal charge)

The results of the Kruskal Wallis difference test with the value of asymptote strengthen the difference in understanding between these groups. Sig. 0.00 < 0.05. This value infers a difference in Lewis structure understanding between 1st, 2nd, and 3rd-year students.

However, the advantage of the 3rd-year students over the other two groups is based on the answers' completeness, as presented in Figure 2.

Both 3rd and 2nd-year students answered correctly for the central atom of the AsH_3 molecule (a) and drawing its Lewis structure (c). However, when responding to the coordination number of the central atom (b), the 2nd-year student provided an incorrect answer. They may consider the number of bonding electrons as the coordination number. For formal charge (d), the 2nd-year student leaves the answer empty, implying a lack of knowledge.



(a) (b)

Figure 2. Students' Answers to a Lewis Structure Question (a) 2nd, (b) 3rd Years
(a. Central atom of AsH_3 ; b. Coordination number of the central atom; c. Lewis structure; d. Formal charge)

3.2. Students' Understanding of the Topic of Molecular Geometry

Students' knowledge of Valence shell electron pair repulsive (VSEPR) contributes and correlates to their understanding of Geometry molecule. The VSEPR theory is used to predict the shape of the molecules from the electron pairs that surround the central atoms of the molecule. It is crucial to understand the idea of VSEPR interaction when talking about the structural features of molecules (Liu, 2005). Several tools, including hands-on and virtual, mainly 3D, could be excellent devices to uncover students' ideas about the topic. Hervas & Silverman (1991) employed magnetic stir bars, styrofoam balls, and an overhead projector to reveal students' views of VSPER theory. In our current study, we utilised a computer-based and hands-on model for facilitating students with different levels of scientific reasoning skills in stereochemistry classes (Kusumaningdyah et al., 2023).

A slightly different trend is observed in students' understanding of molecular Geometry. However, molecular geometry may be more difficult for students than the Lewis Structure. In this topic, the 3rd-year students demonstrated the highest average score with 93.20, while the 1st-year was the lowest with 65. A similar trend is also shown for the lowest scores for each group. A different phenomenon is again exhibited for the highest score between groups. The 3rd and 1st-year students have the same highest score of 100. Meanwhile, the highest score for 2nd-year students was 92.

Table 3. Comparison of Students' Understanding of Molecular Geometry

	N	Lowest score	Highest score	Average score	Standard Deviation
1st-year	36	0	100	65	20.48
2nd-year	29	40	92	70.88	10.56
3rd-year	23	76	100	93.20	7.92

Significant differences are observed for the lowest score, with some 1st-year students producing none of the correct answers. Meanwhile, the lowest scores for 2nd and 3rd-year students are 40 and 76, respectively. The result also confirms the advantage of 3rd-year students over the 2nd and 1st-year students. The Kruskal-Wallis difference test with the value of Sig. 0.00 < 0.05, reveal the differences in understanding of Molecular Geometry among 1st, 2nd, and 3rd-year students. An example of students' answers for each class is provided in Figure 3. The scores for 1st-year students are more dispersed while the 3rd-year is clustered close to the mean (93.20).

All three groups of students provided the correct molecular geometry of CHBrClF, which is tetrahedral. However, the 3rd-year students (Figure 3. c) also present the molecular geometry to display the 3D orientation. The 2nd-year students correctly provided the molecular geometry of the molecule (tetrahedral) but did not follow it up with the molecular drawing. On the other hand, 1st-year students do not present the correct name of molecular geometry but draw the Lewis structure only, not the geometry. Kiernan et al. (2021) found that in predicting molecular geometry, several students, while being taught the VSEPR theory and its application to finding analytical answers, instead chose to rely on more illustrative and intuitive modes of thinking.

Regarding the number of free electron pairs in the molecule, the 1st and 3rd-year students considered 0 free electron pairs while the 2nd-year considered nine pairs. This could be rooted by the 1st and 3rd-years only counting the free electron pair for the central atom, while the 2nd-year involved the three atom terminals. Kaufmann et al. (2017) propose that it might be helpful for students learning to draw Lewis structures if the formal procedure was formally taught as a construction, checking, and modification process. Doing so may help students learn to verify that the generated structure is correct, considering circumstances beyond those covered by the octet rule and formal charge.

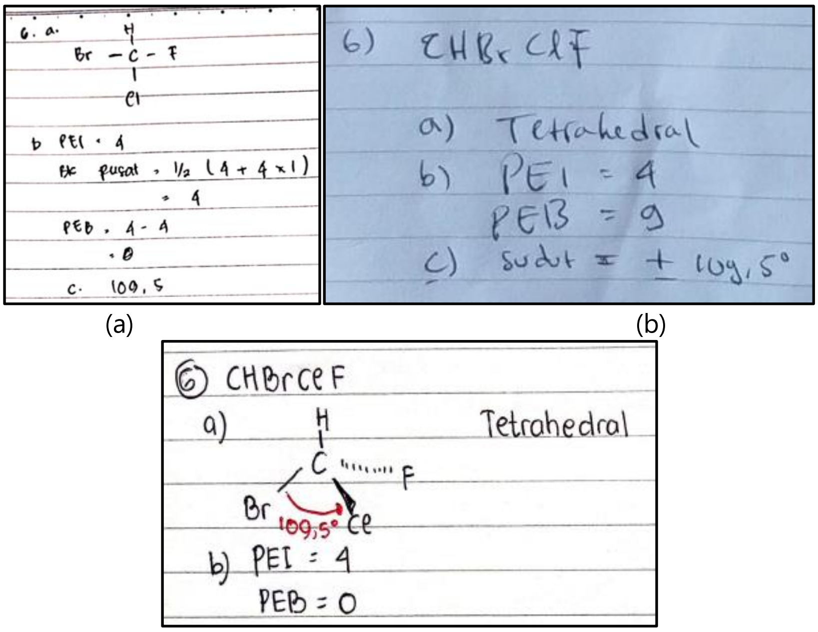


Figure 3. Students' Answers to a Molecular Geometry Question (a) 1st, (b) 2nd, (c) 3rd Years
(a. Molecular geometry; b. Number of electrons in covalent bonds and lone pairs; c. Angle)

3.3. Students' Understanding of Symmetry

A description of the understanding of 1st, 2nd, and 3rd-year students on the topic of symmetry is contained in Table 4. The 2nd and 1st-year students performed equally for the lowest and highest scores, but the 2nd-year surpassed the 1st-year students' average scores. Again, the 3rd-year students overpower the other two groups in all aspects, including the lowest, the highest, and average scores.

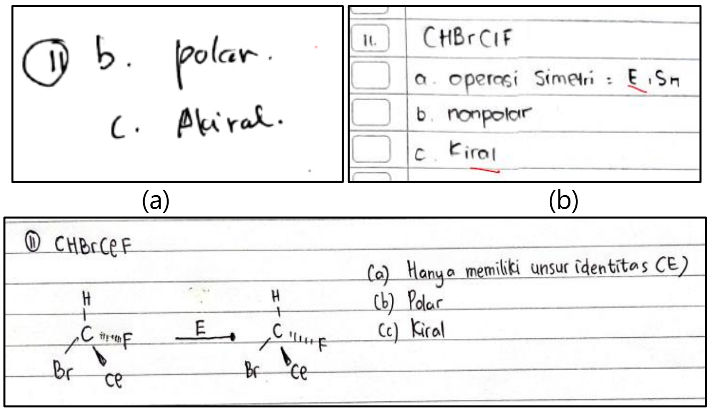
Figure 3 compares students' answers to the symmetry question for the three groups. The 1st-year students demonstrated a very low understanding of symmetry. The finding implies that the student's understanding of symmetry for the two groups follows the order of 3rd > 2nd > 1st. The results of the Kruskal-Wallis test with the value of Sig also confirm the difference. 0.00 < 0.05.

Table 4 implies that the topic of symmetry is the most difficult compared to the two previous topics. Some students scored the highest (100) for the Lewis structure and molecular geometry but none for the symmetry. Also, some 1st and 2nd-year students provided all incorrect answers for the symmetry questions. Both the 1st and 2nd-year students got the highest score of 84.44. But, referring to the enormous gap between the average and most elevated scores and the significant standard deviation, the number of students with such scores and around is small. Mental manipulation of molecules is necessary to study molecular symmetry to identify symmetry elements and the corresponding symmetry operations. Students have difficulty engaging in these mental processes in a traditional classroom setting where teachers primarily focus on imparting knowledge through definitions and examples (Rattanapirun & Laosinchai, 2021).

Table 4. Comparison of Students' Understanding of Symmetry

	N	Lowest score	Highest score	Average score	Standard Deviation
1st-year	36	0	84.44	34.62	28.44
2nd-year	29	0	84.44	48.66	20.35
3rd-year	23	40	95.55	75.93	12.93

Their low spatial abilities may influence students' mistakes in answering the question (Figure 4). Some previous pieces of the literature confirmed that only students with high visual-spatial abilities would succeed in understanding molecular symmetry well (Achuthan et al., 2018; Rahmawati et al., 2021; Tuvi-Arad & Blonder, 2010). Low visual-spatial ability will lead to difficulty in understanding symmetry. The spatial ability allows students to visualise molecules from different perspectives and imagine the movement of molecules well when subjected to surgery.



(a) (b)

(c)

Figure 4. Students' Answers to a Molecular Symmetry Question (a) 1st, (b) 2nd, (c) 3rd Years

On the other hand, students with low spatial appearance generally cannot construct internal representations of three-dimensional forms correctly (Harle & Towns, 2011). As a result, students cannot accurately identify the symmetry operations in a molecule. Insufficient formal thinking skills leading to difficulty in building, manipulating, and visualising the movement of an object (Barke & Engida, 2001) could also be the reason for this difficulty. In another study (Carlisle et al., 2015), Students practised their skills in identifying symmetry planes on 3D molecular models/geometries and visualising them on 2D VSEPR representations by analysing these objects for symmetry. Students' innate spatial awareness was bolstered by the process of identifying symmetry planes, which gave them a reason to evaluate constructions from a variety of angles. The complexity of the interplay between the VSEPR, Mulliken-Walsh, and electrostatic force theories, as well as the myriad other elements that affect molecule geometry, should be emphasised to students (Desseyn et al., 1985).

3.4. The Correlation of Students' Understanding of Lewis Structure, Molecular Geometry, and Symmetry

Spearman Rank correlation is used to test the correlation of students' understanding of each topic. Table 5 describes the correlation between students' understanding of topics. The test result confirms a positive and strong relationship between students' knowledge of Lewis structure and molecular geometry for the three groups of students with ρ values of 0.979, 0.979, and 0.966 (< 0.01) for 1st, 2nd, and 3rd-year students, respectively. Students' understanding of molecular geometry also correlates positively with their understanding of symmetry. Students' understanding of Lewis structure and symmetry also demonstrates a similarly strong correlation.

When the correlation was tested simultaneously for all the students, it also confirmed the result of the separate group measurement. These results establish that understanding of Lewis structure and VSEPR to molecular geometry, molecular geometry and symmetry, and Lewis structure and symmetry. Considering this positive correlation, emphasising students' solid knowledge of Lewis structure is the strong foundation for concept acquisition of molecular geometry and symmetry. Therefore, university educators should emphasise the robust initial understanding of Lewis structure and molecular geometry to build a successful symmetry teaching. Moravcová et al. (2021) stated that in light of the preceding, we propose the following pedagogical changes: more attention should be paid to non-models and figures in non-prototypical positions in textbooks and instruction; the use of atypical tasks in mathematics classes (e.g., investigating symmetries of not only 2D, but also 1D figures); the inclusion of elementary tasks on symmetries in instruction, even at the upper levels of schooling; and, finally, greater emphasis should be placed on the focus of pre-service teachers' conceptual knowledge and implementation of spiral curriculum across the entire educational process. Savchenkov (2020) proposed that large numbers of 3D-printed models of molecules be used in preassembled sets to teach students about molecular structure, symmetry, and related topics. Students in a course on molecular structure were very positive toward 3D printing, believing that it helped them better grasp the material (Niece, 2019).

Table 5. Correlation Test of 1st-Year Students' Understanding

Topic	1st-year	2nd-year	3rd-year	Conclusion
Lewis Structure, VSEPR, and Molecular Geometry	ρ = 0.979	ρ = 0.979	ρ = 0.966	Positive relationship
Molecular Geometry and Symmetry	ρ = 0.986	ρ = 0.986	ρ = 0.966	Positive relationship
Lewis Structure and Symmetry	ρ = 0.981	ρ = 0.981	ρ = 0.924	Positive relationship

4. Conclusion

This study's results show differences in understanding of Lewis structure, molecular geometry, and symmetry between the 1st, 2nd, and 3rd-years students. The 3rd-year students always performed better than the 1st and 2nd-year students for all three topics. This study also found a positive and strong correlation between understanding lewis structure, molecular geometry, and symmetry. Based of these results, it is highly recommended that university chemistry lecturers be aware of the hierarchies importance of Lewis structure, VSEPR, molecular geometry, and symmetry.

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