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Students' mental models for molecular geometry concepts: A multiple-representation perspective

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Abstract: This research aimed to explore the mental model of high school students' understanding of the molecular geometry concept from the perspective of multiple representations. This research used an explorative survey with a qualitative approach involving 20 participants selected using purposive sampling. The data analysis carried out was an iterative content analysis to determine a consistent pattern in the participants' answers. The results of this study revealed that there were approximately 33% of students in the target mental model (TMM) category from the aspect of symbolic representation within the concept of writing electronic configurations, writing Lewis structures, and determining the number of PEB and PEI. In the aspect of submicroscopic representation, there were 5% of students with the target mental model category (TMM) within the concept of VSPER theory and 35% of students with the target mental model category (TMM) within the aspect of macroscopic representation, particularly in the compound polarity concept. Additionally, two students showed an unexplored mental model (UMM). These findings arose due to the large number of students who have mixed mental model (MMC) and alternative mental model (AMM) categories.

Keywords: *high school, molecular geometry, mental models, multiple representations*

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INTRODUCTION

Chemical properties can be viewed as multiple levels of representation. Multiple levels of representation include macroscopic, submicroscopic, and symbolic (Hafsah, Hashim, Zurida, Jusoff, & Yin, 2014). Chemical concepts that provide multiple representations need to be studied because it is difficult to understand the next concept if the initial concept has not been mastered. The representations that are often raised by teachers in the learning process tend to be symbolic and macroscopic aspects, while submicroscopic aspects are rarely raised. This could be due to difficulties in visualizing structures, behaviors, and processes occurring at the particulate level and connecting them to the macroscopic level (Fratiwi, Utari & Samsudin, 2019).

The chemistry learning process should link the three levels of representations. However, students have difficulty understanding the levels of submicroscopic and symbolic representations because these two representations are invisible and abstract (Ramnarain

& Joseph, 2012; Towns & Nicole, 2015). Most chemistry concepts are abstract (Zoller, 1990) and some students have difficulties understanding their concepts (Özmen & Ayas, 2003). Students tend to memorize submicroscopic representations and abstract symbolic representations resulting in students not being able to imagine how the processes and structures of a substance undergo a reaction (Talanquer, 2011).

The chemistry learning instruction requires a good student's understanding of the chemistry concept. The student's understanding of chemistry concepts can be viewed by the multiple representation levels. A recent study showed that the use of multiple-representation instruction leads to the improvement of students' concept understanding (Abdurrahman, Liliasari, Rusli, & Waldrip, 2011). The multiple representation levels consisting of macroscopic, sub-microscopic, symbolic (e.g. Kozma, 2003; Treagust, Chittleborough, & Mamiala, 2003; Gilbert & Treagust, 2009) and mathematics (Hafsah, *et al*., 2014) can be used to describe the chemical concept. The first is the macroscopic level which represents the chemistry concept obtained by the experience or experiment (Li & Arshad, 2014). Johnstone (2000) proposed that the macroscopic level can be seen, touched, and felt. The second is the sub-microscopic level which is identified as the chemical representation in the form of the visualization including the atom, ion, and molecule in the chemical reaction (Bucat & Macerino, 2009). Davidowitz, Chittleborough, and Murray (2010) state that the representation of the sub-microscopic level is expected to provide a complete description of the chemical reaction. The third is the symbolic level which represents the chemistry that consists of the symbol or icon as a tool to describe the atom, its characteristics, phase, and the equation of chemical reaction (Talanquer, 2011). This symbolic description includes the writing of the element, compound, substance phase, graphics, and table representation, and also equal chemical equation. The ability to represent has an important role in studying chemistry due to the fact that chemical representation is a means for students to solve chemistry problems (Madden, Loretta, & Jrene, 2011).

An understanding of the three levels of representations is termed as a mental model (Jansoon, Coll, & Samsook, 2009). A mental model can be a picture of an idea, experience, and model in someone's mind that they have experienced before (Chittleborough, Treagust, & Mocerino, 2002). Students' mental models are formed when they absorb new ideas and provide information that can be accepted or recognized (Amalia, Ibnu, Widarti, & Wuni, 2018). The cause of the student's mental model is not intact because of the difficulty of students in understanding the concept of abstract multiple representations that are imperfect (Stains & Sevian, 2015). The topic of molecular shapes is mostly abstract and needs to be supported by visualizing abstractions in various representations in achieving a conceptual understanding. One of the obstacles that students encounter in studying the shape of a molecule is the difficulty in imagining a three-dimensional picture of the shape of a molecule (Barak & Hussein, 2009; Nahum, Mamlok-Naaman, & Hofstein, 2007). The abstraction of the molecular concept is one of the causes of students' difficulties in understanding the description of molecular shapes. The difficulties of students in transforming the three levels of chemical phenomena are because they are not being trained in learning with submicroscopic representations (Davidowitz *et al*., 2010). For students' understanding of chemical concepts to become a unified whole, it is necessary to use the mental model in connecting the three levels of chemical phenomena (McBroom, 2011). The following research question guides the study: "At which level do the students' mental models based on multiple representation abilities in molecular geometry topics?"

METHOD

This research adopted an explorative survey with a qualitative approach focusing on exploring the meaning of high school students' experiences in learning the material of molecular geometry. Data collection was carried out without any treatments but in a natural setting. Researchers collected information related to the problem to be studied in full by using various data collection procedures based on a predetermined time. This research was conducted in class X high school in the city of Yogyakarta, Indonesia with the total of 20 students (11 female and 9 male). The selection of participants in this study was based on a purposive sampling technique under the criteria that students had studied the topic of molecular geometry and were willing to become participants. The mental model expressed by students on the concept of molecular geometry was the unit of analysis in this study. Analyzing their responses and the reasoning behind their responses allowed the researcher to identify their reasoning patterns and how they comprehended the molecular geometry concepts.

Data collection was carried out using a combined technique that was triangulation. Identification of students' mental models was done through the provision of open-ended responses, clinical interviews, and previous research related to students' conceptions of molecular shapes (Dean & McIndoe, 2016; Karacop & Doymus, 2013; Clauss *et al.*, 2014; Erlina, Cane & Williams, 2018). The questions in the interview were questions asked in an open response, then the interview was deepened by asking questions about the reasons for the participants' answers to open responses so that in clinical interviews there were only guidelines for possible questions. An example of the question given was ''What do you think is meant by the molecular geometry of type AX_5E in BrF_5 compounds? Can you describe the molecular geometry of the compound?''. Clinical interviews were then conducted with participants who had been selected purposively. The clinical interview lasted about 30-40 minutes. The purpose of this exploration through open-ended responses and interviews in the form of clinical interviews was to identify as many participants' mental models as possible.

In this study, data content analysis was carried out with interpretive inductive techniques. Analyzing their responses and the reasons behind their responses allowed researchers to identify their reasoning patterns and how they understand the concept of molecular shape. Since mental models were considered personal, internal representations might reflect the learner's subjective world (Gilbert & Boulter, 1998; Greca & Moreira, 2002). Interpretive qualitative methods were appropriate for obtaining the rich descriptions necessary to elicit and understand learners' mental models. Eliciting mental models required determining consistent patterns in participants' responses; therefore, most researchers had placed stronger emphasis on analytical inductive analysis methods. There were six basic steps followed in the analysis of this research data, namely organizing and preparing data for analysis, reading all data, coding the data, generating themes or categories from codes, organizing and describing the data in terms of codes and themes, and interpreting the data.

This research used primary data sources obtained directly from participants through open-ended responses of a mental model. Before analyzing the results of the open-ended responses, the following data collection technique was conducted first, namely the process of interviewing using a clinical interview guide. The research data obtained was subjected to reliability testing. The reliability test in this study was carried out through a Focus Group

Discussion (FGD) in the same group transcript forum (the experts were given the results of this research data analysis). This test was carried out by four experts to find the meaning of the research theme and reach a common agreement between the experts and the researcher. The coding results of the analysis based on the review of open-ended responses of the mental model and the clinical interview results that had been coded by the researcher would then be discussed by the four experts in the FGD process.

The classification of mental models referred to several predefined theories, namely the concepts of Coll and Treagust (2003), and Park and Light (2008), and elaborated with concepts (Körhasan & Wang, 2016) and further developed by researchers. The following was a classification of mental models that emerge from the coding process in this study, namely the Target mental model (TMM), partial mental models (PMM)**,** the mixed mental model (MMM) was developed by researchers because several student answers had misconceptions so that the answers given were not perfect, alternative mental models (AMM)**,** the unexplored mental model (UMM) was developed by researchers because students did not give any response at all in open-ended responses and clinical interviews.

FINDINGS AND DISCUSSION

In the data coding stage before FGD, there were 75 concept codes with details of 36 target concept codes and 39 alternative concept codes for 5 molecular shape concepts. Through the FGD stage, inputs were obtained regarding several concepts, resulting in a change in the number of concept codes to 67, with details of 30 target concepts and 37 alternative concepts. Additionally, the experts suggested that data that could not yet be coded should be labeled as "underachievement" if the participant's response was outside the expected answer but not by the correct concept, and labeled as "higher achievement" if the participant's response was outside the expected answer but by the correct concept.

Classification of the target mental model (TMM) for participants who have the same number of target concept codes as the target concept code should be in the question number. Partial mental model classification (PMM) for participants who only have a partial target concept code of what the target concept code should be. Mixed mental model (MMM) classification for participants who have both target and alternative concept codes. Classification of alternative mental models (AMM) for participants who only have alternative conceptual codes. Classification of unexplored mental models (UMM) for participants who do not have both concept codes, both target and alternative concept codes. Identification of students' mental models can be done by knowing students' understanding in terms of three levels of chemical representation (Jansoon, *et al*., 2009). The representational ability of students in this study can be seen through the results of the mental model classification recapitulation in Table 1. Students who have a target mental model (TMM) mean they have

Table 1
Recapitulation of students' mental models on the concept of molecular geometry

Multiple Representation	Classification of Mental Models (%)				
	TMM	PMM	MMM	AMM	UMM
Simbolic	31.25	21.25	30.00	17.50	-
Submicroscopic	2.50	3.40	32.50	60.00	-
Macroscopic	50.00	30.00	10.00	10.00	-

a complete understanding of the level of representation while students who do not have a target mental model (TMM) mean they do not have a complete understanding of the level of representation termed non-representation in this study.

Based on Table 1, the level of symbolic representation in this study includes three concepts of molecular shape, namely the concept of writing the electronic configuration of an element, the concept of describing the Lewis structure of a compound, and the concept of the number of bonding electron pairs and non-bonding electron pairs. Based on the results of the student's mental model recapitulation in Table 1, students who have an understanding of the symbolic representation level are those who belong to the target mental model classification (TMM) for these concepts. Based on the recapitulation of mental model classification, it was found that 31.25% of students have a complete understanding of the symbolic representation level, while the remaining 68.75% were obtained from students who had partial mental model classification (PMM), mixed mental model (MMM), and alternative mental model (AMM). Furthermore, the submicroscopic representation is the level of representation that students use when applying knowledge from their learning experience to understand abstract chemical concepts. The submicroscopic representation level in this study is found in the concept of determining molecular geometry based on the valence shell electron pair repulsion (VSEPR) theory and hybridization theory.

Based on students' responses through open-ended responses and clinical interviews, it was found that there was one concept that did not appear in the target mental model classification (TMM) at all, namely the concept of determining molecular shapes based on hybridization theory, which means that 100% of the students did not have a complete understanding of this concept. This is due to students' difficulty in understanding the sub-microscopic level representation because it is abstract, resulting in students being unable to imagine the process and structure of a compound (Talanquer, 2011). Regarding the concept of determining molecular shapes based on the VSEPR theory, which is a sub-microscopic level representation, 5% of students were classified as having a target mental model (TMM) for this concept, indicating that 5% of students have an understanding of this level of representation. From the answers given students were able to correctly describe the molecular shape of the BrF5 compound which has a rectangular pyramid shape with the AX5E molecule type. However, there are still many students who do not have an understanding of the sub-microscopic level representation of this concept. A total of 95% of students were unable to correctly determine the molecular shape of a compound. Students who belong to the non-submicroscopic level are those who have PMM, MMM, AMM, and UMM classifications. These students can mention the names of molecular shapes but cannot describe the molecular shape of a compound.

According to students, learning about molecular geometry in chemistry is very difficult to understand which causes a lack of students' interest in learning this concept. This is because students only know theory from books and explanations from teachers (Setiawan, Rostianingsih & Widodo, 2018). In learning the concept of molecular shapes, students do not yet have an extra understanding, as they are not able to imagine the microscopic structure of the molecules in a compound (Ang, Ng, & Liew, 2020). Additionally, teachers do not use pictures as a medium to help with learning chemical bonding. The concept of molecular shapes is difficult to imagine, so students will struggle when trying to learn the theory more realistically. Therefore, an evaluation is needed in the learning process by providing training to the students, especially in solving problems related to VSEPR and hybridization concepts, which are abstract levels of representation. The third representation level is macroscopic representation, which is a level of representation that can be observed directly, such as chemical phenomena in experiments or everyday life (Sanchez, 2021).

The macroscopic representation level is present in the concept of the polarity of a compound's molecule in questions 4, 6, and 8. Based on the results of the classification of mental models, the macroscopic level of representation dominates in 33.3% of students who have the target mental model (TMM). This indicates that students have an understanding of the macroscopic level of representation by explaining the polarity of a compound and describing the differences between polar and nonpolar compounds according to the expected answer. The interconnection of these three levels of representation will contribute to the construction of students' understanding and comprehension of chemical phenomena (Chittleborough, 2004). However, this is also the causes of students finding it difficult to learn chemistry. Gilbert and Treagust (2009) argued that connecting these three levels of representation would greatly help improve students' mastery of chemical concepts. From the results of clinical interviews, students also showed a lack of interest in learning science because they considered it a difficult subject (Abdinejad, Talaie, Qorbani, & Dalili, 2021)

To identify participants' mental models of the concept of molecular shape, their conceptions of molecular geometry were first determined. An initial analysis of participants' responses indicated that they had misconceptions about the molecular shape that were similar to those documented in previous studies (Clauss *et al*., 2014; Erlina, Cane & Williams, 2018; Esselman & Block, 2018; Uyulgan, Akkuzu, & Alpat, 2014). These misconceptions were due to the students' low understanding caused by learning that focused more on two phenomena, namely macroscopic and symbolic, while submicroscopic representation was less emphasized, making it difficult for students to transfer knowledge through interconnections between one level to another. Student's difficulties in transforming these three levels of chemical phenomena were due to their lack of training in learning with submicroscopic representation (Davidowitz *et al*., 2010). To ensure that students' understanding of chemical concepts becomes a unified whole, it is necessary to use their mental models in connecting these three levels of chemical phenomena (McBroom, 2011).

Based on this research, a teacher needs to be able to identify the mental models that their students hold. However, it is not easy to define the mental model of a person that represents the differences in thinking of each individual (Tumay, 2014). Therefore, a review by subject teachers is needed to check back on students' concepts so that the teacher should be able to design a learning process that follows the mental model of the student, including the learning model, approach or strategy, learning media, and textbooks that support the student's mental model (Fratiwi *et al*., 2020).

The still high percentage of participants with alternative mental models indicates that they have not fully used scientific thinking processes when solving problems related to molecular shapes. Some factors that may contribute to this include incomplete understanding, misconceptions arising from participant errors, information from teachers and classroom learning, or learning resources used. This highlights the importance of developing chemistry education that trains students to think scientifically and systematically. Therefore, innovative learning is needed that includes the development of appropriate learning technologies, such as adaptive and interactive learning applications, that can help students obtain better conceptual understanding. In addition, the use of innovative learning approaches, such as multiple representation-based learning, game-based learning, and collaborative learning can help students build good mental models in learning. Thus, students can develop the ability to understand concepts in depth and integrate them and be able to apply them in everyday life.

CONCLUSION

The low occurrence of target mental models among students is caused by the high percentage of students who have mixed mental models (MMM) and alternative mental models (AMM). In addition, there are unexplored mental models (UMM) because students did not respond during open-ended responses and clinical interviews. Students also face difficulties in representing concepts related to molecular shapes, especially in determining molecular shapes based on hybridization theory. This concept involves sub-microscopic representation levels. The absence of target mental model (TMM) classifications on this concept indicates that students seem to not have a complete understanding of sub-microscopic representations related to molecular shapes based on hybridization theory. Chemistry learning with multiple representations helps students to actively express their knowledge of chemical phenomena through proper analysis. Therefore, this research is considered beneficial for students and teachers as a contribution to improving the quality of chemistry learning on the topic of molecular shapes. In addition, this research can be a consideration for researchers to conduct similar research on other topics.

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