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Research Article

Students' Mental Model in Understanding Chemical Bonding and Its Correlation with Chemistry Mindset

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Abstract. This study aims to describe the mental models of secondary school students and examine their relationship with the chemistry mindset. The research involved 122 secondary school students in the 10th, 11th, and 12th grades. Data were collected using a structured descriptive assessment and a chemistry mindset questionnaire. Students' mental models were categorized according to Kurnaz and Eksi's indicators, covering initial, synthetic, and scientific models. Meanwhile, the Chemistry Mindset Instrument employed the framework established by Santos et al. and categorized as fixed and growth mindsets. Pearson's coefficient measures the correlation between the mental model and the chemistry mindset. This study finds that many of the students' mental models fall into initial and synthetic categories, with only a small number in the scientific category. The proportion of students with the synthetic model peaks in the formation of ions at 63.11%, in the initial category of covalent bonding at 54.92%, and in the scientific category of coordinate covalent bonding at 18.85%. Furthermore, this study indicates a weak relationship between the mental model and the chemistry mindset. Students' confidence during chemistry class influences this issue. Therefore, teachers are expected to select appropriate learning models to enhance students' achievement and mindset toward chemistry.

Keywords: fixed mindset, growth mindset, model and modelling in chemistry, non-cognitive factor, visual representation

1. INTRODUCTION

Chemistry concept comprehension will be successful when students can relate to three levels of representation: macroscopic, submicroscopic, and symbolic. However, these levels often become obstacles for students, as submicroscopic representations consist of complex concepts and abstract phenomena that are invisible to the naked eye [1]. Due to their abstract nature, chemistry concepts are often represented through models and modeling [2].

Some chemistry educators have attempted to define the terms "model and modeling." A model represents ideas or a simplification, description, or conception of a particular phenomenon, including systems, processes, situations, and mathematical terms [3]. The effort to describe and construct those models into observable procedures is known as modeling [4].

A mental model is an internal depiction formed when a student encounters a problem. This model can be stored in long-term memory and applied when the student receives a similar task [5]. In simpler terms, a mental model is an individual's view or representation of an object, concept, system, or other phenomenon [6], that is constructed within memory and has been of interest in the areas of cognitive science and science education [7]. Mental models are also described as visualization and understanding that students conduct to elaborate on ideas or notions from previously learned phenomena. Therefore, it can be considered an internal depiction created by an individual while understanding and applying a concept or phenomenon.

In chemistry, the mental model is often explained as an understanding of students toward three levels of chemistry representation [8]. It is related to students' understanding of a concept, which can significantly influence students' academic achievement. Students with a good mental model demonstrated a good understanding [9]. The result of this study can be used as a reference for teachers to understand the difficulties, comprehension, and misconceptions experienced by students [8] and utilize to design a suitable learning model [9]. Students who can already specify their mental model can adapt to their learning style. Therefore, students must possess a model and ability while learning chemistry to help them understand and communicate chemistry [11]. In our previous study, it was confirmed that the identification of students' mental models is essential for chemistry learning [12]. Chemical bonding is a challenging topic for many students. A survey conducted on many secondary school students in Indonesia demonstrated a lack of knowledge and an unscientific understanding of the topic [13] impliying insufficient mental models.

Mental Model and Chemistry Mindset

Some experts classify students' mental models into several categories, including scientific, synthetic, and initial models [13]; scientific, phenomena, symbol, and inference characteristics [14]; macroscopic, submicroscopic, and symbolic [8]; No Response (NR), Specific Misconception (SM), Partially Correct (PC), and Scientifically Correct (SC); referent, relation, syntax, result, and sensemaking process [15]. Among these categories, this study applies the categorization proposed by Kurnaz and Eksi [13], as it provides comprehensive criteria and a fair scoring system to analyze mental models based on descriptive responses and visualizations performed by students. Because the nature of mental models is complex and variable, analyzing mental models requires comprehensive data gathered from students in the form of pictures, writings, and verbal explanations [16].

A scientific mental model represents a perception that aligns with the nature of concepts recognized by the scientific community. A synthetic model partially aligns, while initial models do not align with the accepted understanding in the scientific community. The criteria for these categories are specific to each chemistry concept. For example, regarding molecular polarity, the attributes of students' mental models—whether scientific, synthetic, or initial—depend on their understanding of molecular geometry and its effect on the resultant vector of bonding moments around the central atom. For this reason, this platform is adopted in this study due to its relevance to the need for enhancing students' understanding of chemistry.

Kurnaz and Eksi [11] stated that a person's mental model can be revealed through the expression or action that reflects their comprehension of a particular concept. That is why each student will have a unique mental model, as they hold different scientific perspectives on a phenomenon. Several factors contribute to the unique mental model possessed by each individual, including formal instruction (teacher explanations), textbooks, language, social environment, and student intuition [14]. Additionally, factors that influence the development of mental models include age, scientific thinking skills, and learning experiences. The older an individual is, the more complex the mental model will be; in other words, it will be a more scientific mental model [17]. According to previous studies, student grade level also affects the development of their mental models. Students in the third year of secondary school will have a better mental model than first- or second-year students.

Apart from the mental model, the drive from students themselves, including mindset, motivation, and other non-cognitive factors, is the most prominent factor to promote student success in chemistry [18], [19]. Mindset theory describes a belief system that varies depending on context, specifically concerning how much intelligence can be changed through effort [20]. Mindset is one of the non-cognitive factors that determine students' academic achievement. It refers to a way of thinking, self-efficacy, and goal orientation [21] that enables individuals to obtain, process, investigate, interpret, and elaborate on the phenomena they experience. Mindset is categorized into two main types: a fixed mindset and a growth mindset. A fixed mindset is held by students who believe that human intelligence and ability cannot be changed or developed. In contrast, a growth mindset is characteristic of students who believe that intelligence is a trait that can be cultivated and enhanced through effort and guidance from a tutor. Students who learn chemistry will adopt a specific mindset known as the chemistry mindset. Chemistry mindset refers to a way of thinking or an individual belief about one's ability to manipulate chemistry intelligence through effort [22]. In subjects with a highly demanding context, such as chemistry, students' perceptions regarding their ability to enhance their intellect and mindset likely exert a greater influence on their academic performance [23]. The chemistry mindsets of students may forecast their behavioural reactions to obstacles encountered in a chemistry course [20]. Therefore, understanding students' mental models and mindsets will help chemistry educators deliver effective chemistry instruction. In addition, a fixed mindset is contagious [24], therefore, knowledge of the mindset could assist teachers in preventing the spread of the unexpected mindset.

Research objectives

Efforts to address students' challenges in learning chemistry primarily focus on cognitive aspects, such as intelligence. In particular, chemistry is regarded as a technoscience that merges scientific inquiry with technological objectives [25]. Therefore, this study examined non-cognitive aspects, including mental models and a chemistry mindset, which also contribute to students' proficiency in chemistry. This study aimed to describe students' mental models and chemistry mindsets in chemical bonding. The correlation between the students' mental models and chemistry mindsets was also investigated.

2. RESEARCH METHOD

This study involved 122 tenth, eleventh, and twelfth-grade public secondary school students in Malang, East Java, Indonesia. Mental model indicator from Kurnaz & Eksi [14] was utilized to measure students' mental models using short-answer questions covering elements of stability, the formation of ions, ionic bonding, covalent bonding, coordinate covalent bonding, and metallic bonding. When answering the mental model questions, students were required to generate a visual representation (picture) in response to the verbal answer they provided. Therefore, the assessment of students' answers was measured from the two aspects (scientific reasoning & pictorial relevance). Content analysis, using the parameters in Table 1, was employed to uncover students' mental models.

Table 1. Mental Model Rubric

Criteria	Mental Model Category
Robust scientific reasoning & relevant pictorial representation.	Scientific
Partially scientific reasoning and partially pictorial representation; Partially scientific reasoning and relevant pictorial representation; Robust scientific reasoning and partially pictorial representation;	Synthetic
No answer; No picture; irrelevant pictorial representation	Initial

Meanwhile, the chemistry mindset questionnaire from Santos et al [26] was applied to measure students' chemistry mindset. A 1-10 scale semantic differential was implemented to categorize students' chemistry mindset. The growth mindset is associated with the scale of 6 to 10, while the fixed mindset corresponds to scores below 6. This attitude research instrument requires respondents to articulate their attitudes concerning two opposing adjectives [27]. Meanwhile, Pearson correlation analysis was used to determine the relationship between the mental model and the chemistry mindset. This correlation test was carried out after the prerequisite tests (normality and homogeneity) were met.

3. RESULT & DISCUSSION

Description of Students' Mental Models Across Cohorts

Figure 1 depicts the percentage of students with a specific mental model for the tenth, eleventh, and twelfth grades. It illustrates a particular development of mental models tailored to grade level. The figure indicates that the initial mental model, representing the lowest level, is most prevalent among 10th-grade students. This is also the highest initial level across the three cohorts, comprising more than half. The number of students with a synthetic model in this cohort is lower than that of the initial model. However, the number of students demonstrating the scientific model, which is the most expected, is very low, at below 5%. This suggests that most 10th-grade students still lack a sufficient mental model.

The 11th-grade students demonstrated a similar trend to the previous cohort. The number of students with initial and synthetic mental models in this cohort is almost the same, with the latter being slightly higher. The number of students with scientific mental models is slightly higher than in the 10th grade, but the difference seems insignificant. All in all, this cohort's slightly higher mental model status still does not seem promising.

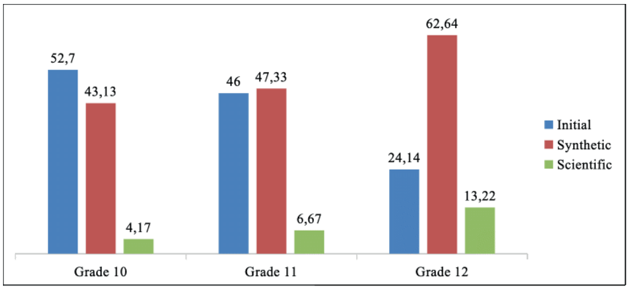

Figure 1. Number of students with the mental model level for each cohort

The twelfth-grade students demonstrated a superior mental model status compared to the other two cohorts, as evidenced by the number of students with scientific mental models (13.22%), which doubled that of the others. The number of students with an initial mental model for this cohort is also relatively small, with less than a quarter. It is revealed that the mental model of twelfth-grade secondary school students is more advanced than that of tenth and eleventh-grade students. It can be used as evidence that an improvement in scientific thinking skills will accompany a student's higher grade level. As stated in a previous study, better scientific thinking skills are a result of student mental model improvement [16]. Learning experiences also contribute to the development of a student's mental model. This implies that students' physical maturity may influence their mental models. This is following the previous study's finding that the older the individual, the closer their mental model is to a scientific mental model type [28]–[30]. The third-grade student who has already studied chemistry for three years has more experience and exposure to chemistry teaching, which may help them formulate chemistry concepts into a more scientific mental model [30].

Description of Students' Mental Models Across Topics

Students' mental models in this study are explicitly described for each topic (Table 2). The data were obtained from all cohorts combined. The table indicates that the highest scientific mental model was observed in coordinate covalent bonding, with nearly one-fifth of the total students. A significant number of students also demonstrated an understanding of scientific mental models in ionic formation and bonding. Meanwhile, almost none of the students exhibited a scientific mental model in covalent and metallic bonding. Unfortunately, most students are in the synthetic or initial mental model for all topics. This implies the need to consider this issue in chemistry teaching in an appropriate manner. A similar study conducted in Indonesia involving prospective chemistry teachers in the school chemistry topic demonstrated comparable results with medium average scores [31], suggesting initial or synthetic models.

Table 2. Number of students with the mental model level for each topic

Sub-Topic	Scientific (%)	Synthetic (%)	Initial (%)
Element Stability	4.10	43.44	52.46
Ionic formation	9.84	63.11	27.05
Ionic Bonding	7.38	52.46	40.16
Covalent Bonding	0.82	44.26	54.92
Coordinate Covalent Bonding	18.85	42.63	38.52
Metallic Bonding	0.00	45.90	54.10

The insufficiency of students' mental models must be considered because it also reflects their understanding of relevant chemistry concepts. Figure 2 presents an example of a student's initial mental model regarding the stability of elements. *For clarity, the figure is reconstructed from the original manual drawing.* The students' responses indicate a lack of understanding of element stability, as shown by their inability to correctly write down element configurations, grasp how elements achieve stability, and accurately describe electron configurations.

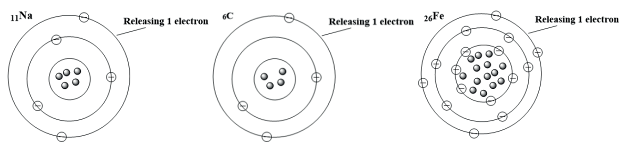

Figure 2. Initial Mental Model on Element Stability

Figure 3 provides an example of a synthetic mental model experienced by 63.11% of students in the context of ionic formation. Like the previous figure, *it is also reconstructed from the original manual drawing.* The figure illustrates the misconception or unscientific understanding regarding ionic formation by depicting a Lewis structure that represents a covalent bond instead of an ionic one. Another unscientific understanding identified in this context is the assumption that the radii of Cl^- and Cl are the same. These two samples confirm the linear relationship between the insufficient students' mental models and their difficulties in understanding chemical bonding. Another example of unscientific understanding associated with the low mental model level is drawing the Lewis structure for HCl; some students considered a double bond between H and Cl.

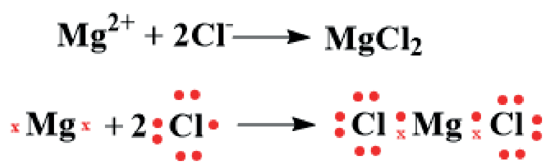

Figure 3. Example of Synthetic Mental Model

Meanwhile, those with a scientific mental model also have a strong scientific understanding of the concept. They understand that the cation radii are always smaller than that of the neutral atom due to the strong interaction between the proton and the outer electron after releasing one electron. Conversely, for a similar reason, the anion radii are always larger than those of its atom. Students with this mental model also provide an accurate drawing of the Lewis structure. These findings suggest the need to enhance students' mental models in order to improve their understanding of chemical bonding and other chemistry concepts. This finding aligns with a previous study that found an unscientific understanding of atomic spectra led to the formation of an unexpected mental model [32]. In a broader perspective, some variables, including prior knowledge, motivation, and learning environment, could affect students' mental models [33].

Description of Students' Chemistry Mindset

Students' chemistry mindset was measured using the instrument of Santos et al [26]. Table 3 describes the indicators of students' chemistry mindset. The mindset is measured using a semantic differential ranging from 1 to 10. Table 3 demonstrates the average value of students' chemistry mindset, which is 6.41. It reveals that students in secondary school tend to have a developing mindset, also known as a growth mindset. Students with a growth mindset will always try to increase their intelligence. They are likely to face challenging tasks by using new strategies that will lead them to successful academic achievement [22].

Table 3. Student Chemistry Mindset Average for Each Question

No	Question	Chemistry Mindset Average
1	My problem-solving skills in chemistry	6.39
2	My ability to understand concepts in chemistry	6.54
3	My ability to apply chemistry knowledge	6.20
4	My ability to comprehend chemistry content	6.39
5	My ability to visualise chemical structure and process	6.29
6	My ability in reasoning and logical thinking in chemistry	6.66
7	My overall chemistry intelligence	6.43

Table 3 also shows that the distribution of students' chemistry mindsets across all indicators is equal. The average score of students' chemistry mindset is 6.41, which tends to fall in the growth mindset. This is in line with the work of Wichaidit [18], the majority of secondary school students in Thailand demonstrated a growth mindset, with almost 70% exhibiting this attitude and only a small portion showing a fixed mindset. Although the score indicates a positive result with a value greater than 6, students' chemistry mindsets still need empowerment to reach the peak point of 10. Students may still consider chemistry a challenging subject. Strengthening this aspect in chemistry students is essential because students' perceptions about their capacity to enhance their intelligence, mindset, presumably, exert a greater influence on their academic performance in demanding educational settings, such as chemistry [26].

Correlation Between Students' Mental Model and Chemistry Mindset

The aforementioned explanation implicitly mentioned that students' mental models correlate positively with the chemistry mindset. The dominant students' mental model at the initial and synthetic levels is relevant to the students' chemistry mindset status, with an index of 6.41. The statistical test using Pearson's Correlation, presented in Table 4, confirms this.

Table 4 presents the correlation test with a value of 0.288, indicating a positive correlation between the mental model and chemistry mindset. However, the correlation index reveals that this correlation falls into a weak category [35]. The correlation result is supported by the observation that students with strong mental model criteria do not always possess a good chemistry mindset. Conversely, some students with a low mental model can still demonstrate a good mindset in chemistry. This weak correlation could also be influenced by other factors, such as students' prior knowledge and the nature of chemistry concepts. As stated in a different study, the effectiveness of mindset intervention depends on its ability to convince participants to alter their mindsets [19]. In our effort to find relevant studies, research uncovering the relationship between students' mental models and chemistry mindsets is lacking. This fact strengthens the novelty of this study.

Table 4. Mental Model and Chemistry Mindset Correlation

		Mental Model	Chemistry Mindset
Mental Model	*Pearson Correlation*	1	.288**
	Sig. (2-tailed)		.001
	N	122	122
Chemistry Mindset	*Pearson Correlation*	.288**	1
	Sig. (2-tailed)	.001	
	N	122	122

Similar studies report on the correlation between mental models or chemistry mindsets and other aspects. Demirdogen & Lewis [20] stated that the theory of mindset suggests that students who possess a growth mindset will achieve higher academic success compared to those with a fixed perspective. This hypothesis aligns with the existing data; however, the changes observed are minimal. The relationship between self-efficacy and formative outcomes was fully mediated by mastery-approach and avoidance goals. However, Mindset was not found to predict formative scores, either directly or indirectly through goal orientations [21]. An interesting finding is reported from the study in the USA [36] who found that a growth mindset positively predicted achievement only among students from economically more privileged families, not among those from less privileged ones. Meanwhile, another study reported that educators with a fixed mindset were more likely to implement performance-oriented instructional strategies, emphasizing interpersonal comparisons. In contrast, those with a growth mindset tended to prefer mastery-oriented instructional approaches, focusing on the enhancement of individual skills [37].

Regardless of this weak correlation, effort is required to promote students' mental models and chemistry mindset. Amalia et al. [8] was successful in improving student mental models by applying the cognitive apprenticeship learning model. Moreover, a student's mindset can be transformed into a growth mindset with high learning motivation. This serves as a nudge for teachers to adjust their learning processes effectively, ensuring that the student's mental model and chemistry mindset align in the same direction. Some alternatives to enhance the student's mental model and chemistry mindset include applying learning models that improve conceptual understanding and boost student motivation.

4. CONCLUSION

The study revealed that most students' mental models were classified as initial and synthetic, with only a few categorized as scientific. When the mental models were compared across the three cohorts, the twelfth-grade students' mental models outperformed those of the tenth and eleventh-grade students. The number of students with a scientific mental model in this cohort reflects this. The result is unsurprising considering that the twelfth grade has experienced more chemistry teaching than the other two cohorts. Meanwhile, on average, students' chemistry mindset is 6.41, indicating a tendency towards a growth mindset. However, the effort to strengthen the mindset is still substantially required. A weak relationship exists between students' mental models and their chemistry mindsets. This weak relationship complicates the ability of these variables to predict one another. However, support for students' mental models and chemistry mindsets is expected to serve as an alternative means of improving their understanding of chemistry. Chemistry teaching should deliver not only a focus on cognitive factors but also non-cognitive factors such as chemistry mindset, chemistry identity, motivation, and a positive attitude towards chemistry. Following the study by Ronnel et al [36], it is crucial to analyze the interaction between mindsets and socioeconomic circumstances to understand students' motivation, engagement, and achievement.

AI-ASSISTED TECHNOLOGY STATEMENT

While preparing this work, the authors used Grammarly to enhance language clarity and detect and correct certain misspellings. After utilizing this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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