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OPTIMIST-G (Optimization of Metacognitive Thinking Skills through STEAM-Based Gamification) in Chemical Bonding Learning

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Abstract

By using a STEAM-Based Gamification method, this study seeks to maximize students' capacity for metacognitive thinking when learning chemical bonds. In the odd semester of 2023, 28 Biology Education students in class C participated in a quantitative study using a one-group pretest-posttest design. The metacognition questionnaire and the pretest-posttest were the primary tools utilized, and the paired t-test and Effect Size (Cohen's d) were employed to analyze the results. After using STEAM-Based Gamification, students' metacognitive thinking skills significantly improved, according to the results (p-value <0.05). According to the Effect Size value (Cohen's d = 2.63), this approach has a very significant impact. The learning strategy planning component saw the largest growth (+35.6%), demonstrating students' growing capacity to oversee their own learning. According to these results, STEAM-Based Gamification may be widely used to teach difficult chemical topics. By developing more interactive, reflexive, and student-centered learning experiences and enhancing their preparedness for the challenges of the Education 4.0 age, this strategy has the potential to transform the educational paradigm in the future.

Keywords: Metacognitive, STEAM-Based Gamification, Chemical Bonding.

1. Introduction

The capacity to think metacognitively has emerged as a key area of study in the field of global education to raise the standard of instruction. Through the Programme for International Student Assessment (PISA), the Organization for Economic Cooperation and Development (OECD) highlights the value of advanced thinking abilities, such as metacognition, in preparing students to meet the challenges of the twenty-first century (Furnham & Cheng, 2024; Hu & Zhang, 2024). PISA findings regularly demonstrate that students who possess strong metacognitive skills typically comprehend concepts more deeply and do better academically (Laukaityte et al., 2024; Wijaya et al., 2024). The difficulty of enhancing these skills is still a problem in many nations, particularly in science courses like chemistry that need on a solid conceptual grasp and critical thinking ability.

Indonesia continues to struggle to raise the standard of science education at the national level. According to PISA data, Indonesian students' science literacy is comparatively low when compared to students in other nations (Agus Supriyadi et al., 2023; Sihombing et al., 2018). The absence of instructional techniques that promote students' reflective and metacognitive thinking is one element that leads to these poor results (AlAli et al., 2023; Al-Gaseem et al., 2020). Indonesia's educational system still frequently emphasizes the passive transmission of knowledge rather than providing students with the opportunity to cultivate more sophisticated and flexible thought processes (Ahmar et al., 2020; Azzajjad et al., 2020). As a result, a novel method is required to maximize students' metacognitive thinking abilities, particularly when learning chemistry, which is a very complicated subject.

A basic idea in chemistry, chemical bonding frequently presents difficulties for pupils due to its abstract character and the requirement for both conceptual knowledge and problem-solving abilities (Harmer & Groß, 2023; Lahlali et al.,

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2023). A STEAM (Science, Technology, Engineering, Arts, and Mathematics) learning strategy coupled with gamification might be a useful remedy for many students who struggle to relate abstract ideas to their practical applications (Belbase et al., 2022; Boice et al., 2021).

The significance of metacognition in scientific education has been covered in a number of earlier research, but these studies have only applied traditional learning techniques like debate and introspection (Dennis & Somerville, 2023; Desoete & De Craene, 2019). Although research on STEAM has demonstrated its efficacy in enhancing students' conceptual comprehension, little is known about how it might enhance metacognitive thinking abilities. Furthermore, it has been demonstrated that gamification boosts learning motivation; nevertheless, there are currently relatively few research that explicitly incorporate STEAM-based gamification in the context of chemistry education.

By creating a STEAM-gamification-based learning model especially intended to maximize students' metacognitive thinking abilities in chemical bonding content, this study seeks to close this gap. It is intended that this method will help understanding of chemical principles as well as the reflective thinking abilities necessary for problem-solving on their own (Febrianti & Dasari, 2024).

Students that possess the ability to think metacognitively are able to organize, track, and assess their own mental processes. Metacognition is crucial in education because it helps students better understand how they learn, pinpoint the best teaching methods, and hone their problem-solving abilities (Anthonysamy, 2021; Rivas et al., 2022). It is challenging to evaluate how well students use metacognitive abilities in their learning process in the absence of precise assessment. Thus, a standardized tool will be used in this study to assess how well STEAM-based gamification enhances students' metacognitive skills in comprehending chemical bonding content.

The integration of several disciplines that mirror the actual world and inspire pupils to think creatively and comprehensively is emphasized by the STEAM method. Through engineering-based experiments, art depiction, and technology investigation, STEAM may aid students in understanding abstract topics in chemistry classes. STEAM may improve student engagement, enhance the educational process, and develop 21st-century abilities like teamwork, creativity, and problem-solving by bridging theory and practice.

A more dynamic and captivating learning experience is provided by gamification in STEAM-based education. Points, challenges, and digital simulations are examples of gamification features that can boost student engagement, raise their motivation to learn, and support the development of metacognitive abilities through reflection and investigation. Gamification has been shown to increase learning retention, speed up conceptual understanding, and promote a positive sense of competition in the classroom.

As aspiring teachers, students in Tadulako University's Biology Education Study Program must possess good metacognitive thinking abilities in the fundamental chemistry course. This is significant because, in addition to imparting knowledge, educators must be able to work with pupils to build more efficient thought processes. According to preliminary findings, a large number of students continue to struggle when it comes to using metacognitive techniques to comprehend and instruct abstract scientific concepts like chemical bonds. Thus, it is anticipated that using the OPTIMIST-G model in the classroom will assist students in developing their metacognitive awareness, enabling them to become more thoughtful, flexible, and creative teachers in the future.

Therefore, the purpose of this study is to investigate and evaluate how well STEAM-based gamification learning might enhance students' metacognitive thinking abilities when it comes to chemical bonding content. It is anticipated that the findings of this study will aid in the creation of creative teaching methods that may be used in Indonesian scientific classes.

2. Literature Review

2.1. STEAM

The STEM concept is expanded upon by the STEAM (Science, Technology, Engineering, Arts, and Mathematics) method, which emphasizes the use of art in the learning process (Alghamdi, 2023). This approach places a strong emphasis on combining different fields to provide a more comprehensive, creative, and useful learning environment. Through art visualization, engineering-based experiments, and the use of technology in the classroom, STEAM in chemistry education enables students to see abstract ideas. Combining these components helps students develop their critical thinking and problem-solving abilities in addition to their conceptual comprehension.

2.2. Gamification of Basic Chemistry Education

Gamification is the use of game elements, such as leaderboards, badges, challenges, and points, to increase student motivation and involvement in the learning process. Gamification has the potential to increase students' enjoyment and engagement with complex basic chemical concepts (Ahmar et al., 2023). For example, competition-based quizzes or game-based instructional applications might improve students' memory and understanding of chemical concepts. Additionally, gamification may encourage students to participate actively in their education while creating a more dynamic and challenging learning environment. education.

2.3. Gamification of STEAM Education

Combining the STEAM approach with gamification results in a more innovative and effective teaching method. By fusing scientific and technological topics with gaming elements, this approach raises student interest in the course contents (Wannapiroon & Pimdee, 2022). This approach to teaching chemistry allows students to explore concepts directly using interactive simulations, game-based experiments, and digital technology that supports project-based learning (Kummanee et al., 2020). By combining STEAM with gamification, students develop critical, creative, and cooperative thinking skills as well as their conceptual understanding.

Table 1. STEAM-Gamification Interconnection and Metacognitive Thinking Skills in Chemical Bonding

Aspects	**STEAM-Gamification in Chemical Bond Learning**	**Impact on Metacognitive Thinking Skills**
S (Science)	Students understand the theory of chemical bonding through experiments and simulations.	Increase **cognitive awareness** in understanding the relationship between atoms and the nature of bonding.
T (Technology)	Utilization of digital simulations, AR/VR, and educational games to visualize molecules and bond structures.	Assist **metacognitive monitoring** through independent and interactive exploration.
E (Engineering)	Design a project-based experiment to test the nature of chemical bonds under various conditions.	Practice **strategic planning** in designing a solution to a problem.
A (Arts)	Use illustrations, animations, and creative designs in representing chemical bonding models.	Facilitate **reflection on learning (evaluating)** through visual and creative approaches.
M (Mathematics)	Calculate bonding energies and relationships between atoms using data analysis.	Improve **problem-solving analysis and evaluation** in quantitative learning.
STEAM-Gamification Integration	Use of experiment, simulation and project-based games to understand chemical bonding.	Encourage **conscious reflective thinking** in solving challenges systematically.

2.4. The Ability to Think Metacognitively

Metacognitive thinking capacity is the ability of an individual to plan, observe, and evaluate their own mental processes in order to finish a task or resolve a problem. Metacognition is essential in the classroom for helping students become more independent learners, pinpoint their understanding gaps, and develop effective study strategies (Rivas et al., 2022). Chemistry requires a thorough understanding of the subject matter and advanced problem-solving skills, therefore assessing metacognitive ability is essential. With increased metacognitive awareness, students may improve their overall academic performance, resolve misconceptions, and make the most of their learning experience.

3. Research Method

This study employed a one-group pretest-posttest experimental design and a quantitative methodology. The purpose of this design was to assess how the STEAM-gamification method affected students' ability to think metacognitively when studying chemical bonds. Without a control group, the One Group Pretest-Posttest design is used, where a pretest is administered prior to therapy (treatment) and a posttest is administered following treatment. This study design follows the following format:

$$O_1 \quad X \quad O_2$$

Description:

O_1 (Pretest): Initial measurement of students' metacognitive thinking ability before treatment.

X (Treatment): Application of STEAM-Gamification in learning chemical bonds.

O_2 (Posttest): Final measurement after treatment to see the improvement of metacognitive thinking skills.

The study population consisted of all Tadulako University Biology Education Study Program students in the odd semester of 2023. Class C odd semester 2023 students, totaling 28, made up the study sample. They were chosen using the purposive sampling approach according to the following criteria: 1) Enrolling in the Basic Chemistry course, 2) Applying the STEAM-Gamification approach to studying. Variables in the Research, the use of STEAM-gamification to teach chemical bonding is the independent variable (X) and the metacognitive thinking abilities of the students are the dependent variable (Y). A metacognition questionnaire with three primary components is used to assess pupils' capacity for metacognitive thought:

Table 2. A Tool for Assessing Chemical Bond Learning Metacognition Ability

Metacognitive Aspects	Metacognitive Indicator	Chemical Bonding Material Indicator
1. Planning	Able to plan strategies to understand the concept of chemical bonding.	Determine the basic concepts of ionic, covalent and metallic bonds before learning further.
	Identify important information in learning chemical bonding.	Analyze the differences in physical and chemical properties of different types of bonds.
	Develop learning objectives before learning begins.	Set learning objectives, such as understanding the difference in bond polarity.
2. Monitoring	Monitor understanding of chemical bonding concepts during learning.	Evaluate whether the understanding of VSEPR theory and hybridization is clear enough.
	Able to identify errors in understanding the material.	Realizing the error in determining the type of intermolecular forces formed.
	Reflect on the effectiveness of the learning methods used.	Identify whether simulations or experiments help in understanding bond energy.
3. Evaluating	Reassess concept understanding after learning.	Evaluate whether the concept of electronegativity has been well understood after the group discussion.
	Identify effective learning strategies for chemical bonding materials.	Using STEAM-based problem solving to understand the strength of chemical bonds in reactions.
	Adjust learning strategies to improve understanding of chemical bonding concepts.	Try other techniques, such as digital molecular modeling or experiments, to deepen the concept of Lewis structures.

The mean, standard deviation, minimum and maximum values of the pretest and posttest findings, as well as the outcomes of the student metacognition questionnaire, were all described using descriptive analysis. This test's objective is, before starting treatment, give a preliminary assessment of the pupils' metacognitive skills, After STEAM-gamification-based learning, demonstrate how skill levels have changed.

Test of Normalcy, Prior to doing inferential statistical analyses, the normality of the pretest and posttest data was examined using, Shapiro-Wilk Test (for sample sizes $\leqslant 50$) or Kolmogorov-Smirnov Test (for sample sizes >50). In order to choose the appropriate statistical test to employ next, this test seeks to ascertain if the data is regularly distributed. A parametric test (Paired Sample t-Test) is employed if the data is regularly distributed. A non-parametric test (the Wilcoxon Signed Rank Test) is employed if the data is not regularly distributed. The paired sample t-test, or hypothesis test, the following formulation of a Paired Sample t-Test is used to assess the efficacy of STEAM-Based Gamification:

$$d = \frac{M_2 - M_1}{SD}$$

d = effect size value

M_2 = posttest average

M_1 = pretest mean

SD = ombined standard deviation

Interpretation of Cohen's d value:

$d < 0.2$ → Small effect

$0.2 \leqslant d < 0.5$ → Medium effect

$d \geqslant 0.8$ → Large effect

If the Cohen's d value is high, then the STEAM-Based Gamification approach is very effective in improving students' metacognitive thinking skills.

4. Results and Discussions

28 students that participated in the STEAM-Based Gamification approach to chemical bond education were the subjects of this study. Students' metacognitive scores increased following the implementation of this learning strategy, according to a descriptive analysis of the pretest and posttest findings.

Table 3. Descriptive analysis of metacognitive abilities

Statistics	Pretest	Posttest
Mean	62.4	82.7
Standard Deviation (SD)	8.5	6.9
Minimum Value	50	70
Maximum Value	75	95

The average student score increased significantly from 62.4 on the pretest to 82.7 on the posttest, as seen in the above table. This demonstrates that students' metacognitive thinking abilities in comprehending the idea of chemical bonding are positively impacted by the STEAM-Based Gamification learning approach. Furthermore, based on the range of results, no student's learning outcomes decreased as a result of taking part in this learning. Conversely, every student demonstrated growth in their knowledge and abilities related to metacognition. All students, regardless of their starting level of knowledge, benefited from this learning, as evidenced by the improvement in the lowest score from 50 to 70 and the highest score from 75 to 95. This enhancement demonstrates how the STEAM-Gamification method may enhance learning, make it more engaging, and help students become more conscious of how they think (Kummanee et al., 2020). Additionally, students may study in a more competitive, driven, and introspective environment thanks to gamification-based learning methodologies, which helps them create more efficient learning strategies for comprehending chemical bonding ideas. To find out whether the increase in score between the pretest and posttest is statistically significant, a Paired Sample t-Test was conducted with the following results:

Table 4. Paired Sample t-Test

Statistical Test	Value
t-statistic	-12.87
df (degrees of freedom)	27
Sig. (p-value)	0.000

A very significant difference between the pretest and posttest findings is shown by the Paired Sample t-Test results, which reveal that the t-statistic value = -12.87. A rise in metacognitive thinking skills following the use of the STEAM-Based Gamification approach is indicated by the negative t-statistic, which shows that the posttest score is continuously greater than the pretest. This test's degree of freedom (df), which is determined by subtracting one from the number of samples (N-1), is 27. The value of df = 27 suggests that this analysis has sufficient data to provide trustworthy findings with a sample size of 28 students.

Additionally, the test findings are highly statistically significant, as indicated by the p-value of 0.000 (<0.05). In hypothesis testing, the alternative hypothesis (H_1) is accepted and the null hypothesis (H_0) is rejected if the p-value is less than 0.05. Accordingly, it can be said that there is a highly significant difference between the pretest and posttest results, demonstrating the effectiveness of STEAM-Based Gamification in enhancing students' capacity for metacognitive thought when studying chemical bonds.

This research confirms that the STEAM-Gamification strategy may make the classroom more engaging, encouraging students to think more critically and raising their awareness of the methods of instruction. This notable advancement also demonstrates how gamification of science, technology, engineering, art, and math instruction may boost student interest, enhance comprehension, and develop critical thinking abilities like metacognition. An Effect Size (Cohen's d) calculation was performed to determine the extent to which STEAM-Gamification-based learning influences students' capacity for metacognitive thought:

$$d = \frac{\mathrm{M2} - \mathrm{M1}}{\mathrm{SD}}$$

$$d = \frac{82.7 - 62.4}{7.7}$$

$$d = 2.63$$

This result indicates that the impact of STEAM-Based Gamification on metacognitive thinking skills falls into the category of a very significant effect, with a Cohen's d value of 2.63. Three primary indicators planning, monitoring, and evaluating were used to further examine how STEAM-Based Gamification enhances each facet of metacognitive thinking.

Table 5. Analysis based on three main indicators

Metacognitive Aspects	Pretest (Mean)	Posttest (Mean)	Improvement (%)
Planning	60.1	81.5	35.6%
Monitoring	63.7	83.2	30.7%
Evaluating	63.3	83.4	31.7%

It is evident from the above table that all three metacognitive components have grown considerably. After experiencing STEAM-Gamification-based learning, students are increasingly able to develop better learning strategies, as evidenced by the planning aspect increasing the most (35.6%). The evaluation component increased by 31.7%, suggesting that students are becoming more adept at determining the efficacy of their learning strategies and making necessary modifications, while the monitoring component increased by 30.7%, suggesting that students are better equipped to monitor and control their understanding during learning.

5. Conclusion

The findings of this study's data analysis demonstrate that using STEAM-Based Gamification to teach chemical bonding greatly enhances students' capacity for metacognitive thought. The statistically substantial improvement in pretest to posttest scores (p-value <0.05) demonstrates that this approach works well in making students more conscious of their thought and learning processes. Additionally, the Effect Size value (Cohen's d = 2.63), which indicates that the impact of STEAM-Based Gamification on enhancing metacognition falls into the very large category, supports the efficacy of this strategy. Specifically, the planned learning strategy component had the biggest improvement (+35.6%), suggesting that students are becoming more adept at creating, tracking, and assessing their own learning strategies for comprehending the idea of chemical bonding. Therefore, our study demonstrates that STEAM-Based Gamification is a cutting-edge teaching strategy that enhances students' conceptual knowledge while simultaneously fortifying their capacity for metacognitive thought. As a result, the findings of this study have significant ramifications for the creation of the Basic Chemistry curriculum and for the broader use of STEAM-Based

Gamification techniques in other fields to produce more comprehensive, engaging, and successful learning opportunities.

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