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Evaluating the Use of ChemTube3D to Enhance Students' Conceptual Understanding of Nucleophilic Substitution Reactions

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Abstract

The limited use of interactive 3D visual media in higher education chemistry instruction, particularly for topics requiring spatial and dynamic visualization such as nucleophilic substitution reactions (SN1 and SN2), serves as the main issue addressed in this study. This research aims to evaluate the effectiveness of ChemTube3D in enhancing students' conceptual understanding of these reaction mechanisms. A quasi-experimental one-group pretest-posttest design was employed, involving 19 students from the Chemistry Education Study Program. Research instruments included a conceptual essay test consisting of 10 open-ended questions to assess subject mastery, and a Likert-scale perception questionnaire to capture students' responses to the use of ChemTube3D. Data were analyzed using normalized gain (N-Gain) calculations and descriptive analysis. The results revealed a significant improvement in posttest scores, with an average N-Gain of 0.54, classified as moderate. Furthermore, the majority of students responded positively to ChemTube3D, particularly regarding the clarity of reaction visualizations and ease of access. These findings suggest that ChemTube3D is an effective instructional medium for bridging submicroscopic and symbolic representations in complex chemical reactions.

Keywords: *ChemTube3D; Conceptual Understanding; Nucleophilic Substitution; Interactive Visual Media.*

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INTRODUCTION

Organic chemistry is widely regarded as one of the most conceptually demanding subjects in higher education due to its abstract nature, intricate reaction mechanisms, and the necessity to integrate three levels of chemical representation: macroscopic, submicroscopic, and symbolic (Adiska & Musthapa, 2021). Among its many topics, nucleophilic substitution reactions (SN1 and SN2) are considered particularly difficult for students, as they require deep visualization of particle dynamics, reaction intermediates, and transition states. These difficulties are often compounded by the limitations of traditional teaching methods that rely heavily on static diagrams and textbook explanations, which lack dynamic and interactive representations of molecular behavior (Khairani & Prodjosantoso, 2023; Crucho et al., 2020).

To overcome these instructional limitations, educators have increasingly turned to technology-based solutions such as interactive multimedia and 3D visualization tools. One notable example is ChemTube3D, a web-based platform offering dynamic molecular animations, 3D structural visualizations, and real-time simulations of electron movement (Soderberg, 2019; Me & Me, 2022). These features align closely with Mayer's (2009) Cognitive Theory of Multimedia Learning (CTML), which emphasizes that meaningful learning occurs when visual and verbal elements are presented in a coordinated, cognitively efficient manner. The core principles of CTML such as coherence, modality, and spatial contiguity have been shown to reduce cognitive load and enhance students' ability to construct mental models of complex scientific phenomena (Kumar & Santosh, 2022; Theimer, 2019).

A growing body of research supports the pedagogical benefits of integrating 3D and augmented reality (AR) technologies into chemistry education. Systematic reviews by

Khairani and Prodjosantoso (2023) demonstrate how AR-based applications, including virtual laboratories, improve students' ability to visualize abstract chemical processes. Similarly, immersive environments created through AR and VR technologies have been found to significantly increase student motivation and cognitive engagement (Edwards et al., 2018; Hidayah et al., 2020). The specific affordances of tools like ChemTube3D such as the ability to depict transition states, intermediates, and molecular motions offer a significant advantage over conventional static models, supporting more accurate and comprehensive understanding of SN1 and SN2 mechanisms (Pernaa & Wiedmer, 2019; Gök et al., 2025).

Furthermore, research shows that interactive multimedia helps address persistent misconceptions in organic chemistry by clarifying the spatial and electronic factors influencing reaction pathways (Talib et al., 2022; Yang et al., 2018). These technologies promote active learning, enabling students to engage more deeply with content and develop problem-solving skills critical for mastering mechanistic reasoning in chemistry.

Student engagement and perception are also central to the success of multimedia tools in education. According to Davis's (1989) Technology Acceptance Model (TAM), the perceived usefulness, ease of use, interactivity, and motivational appeal of a technology significantly influence its adoption in learning contexts. Empirical studies have shown that AR and 3D platforms enhance usability and motivation by providing intuitive, visually rich, and interactive learning experiences (Yulianti et al., 2022; Wong et al., 2021; Cook & Hest, 2024). In the context of chemistry education, TAM provides a valuable framework for assessing student responses to platforms like ChemTube3D, particularly in terms of how these tools affect their learning motivation and perceived cognitive effort.

Despite growing interest in multimedia applications, there remains a limited number of empirical studies focusing specifically on the effectiveness of ChemTube3D in improving undergraduate students' conceptual understanding of SN1 and SN2 reactions, especially in the Indonesian educational context. Most existing studies tend to focus on general 3D applications or the development of spatial reasoning skills, without addressing the pedagogical impact of specific visualizations on mechanistic understanding.

This study seeks to fill the research gap by investigating the impact of ChemTube3D on both students' conceptual understanding and their perceptions of learning nucleophilic substitution reactions. Conceptual understanding in this context is assessed using indicators adapted from Treagust (1995) and Nakhleh (1993). These indicators include students' ability to coherently explain the mechanisms of SN1 and SN2 reactions, identify the intermediates and relevant reaction conditions involved, explain key influencing factors such as substrate structure, the nature of the leaving group, and the role of the solvent, as well as their capacity to interpret animated visualizations into accurate symbolic representations.

The primary objective of this study is to evaluate the effectiveness of ChemTube3D as an interactive multimedia tool in enhancing undergraduate students' conceptual understanding and perceptions of nucleophilic substitution reactions (SN1 and SN2) within organic chemistry education. Specifically, the study aims to assess students' ability to coherently explain reaction mechanisms, identify intermediates and relevant reaction conditions, analyze key influencing factors such as substrate structure, leaving group, and solvent, and accurately interpret animated molecular visualizations into symbolic representations. Additionally, the study examines students' perceptions of ChemTube3D based on indicators from the Technology Acceptance Model (TAM), including perceived usefulness, ease of use, interactivity, and motivational appeal. By addressing the gap in empirical research particularly in the Indonesian context this study seeks to provide evidence on how technology-based instructional approaches can improve mechanistic understanding and student engagement in complex organic chemistry topics.

METHOD

Research Design

This study employed a quasi-experimental design using a one-group pretest-posttest model. The design was selected due to logistical constraints that prevented the use of randomized control and experimental groups. This model enabled the measurement of changes in students' conceptual understanding before and after the instructional intervention using ChemTube3D.

Participants and Ethical

Approval The participants were 19 undergraduate students enrolled in the Organic Chemistry I course at Universitas NW Mataram during the even semester of the 2023/2024 academic year. Participants were selected using purposive sampling, based on their active enrollment and consistent participation. Ethical clearance was obtained from the Ethical Research Committee of Universitas NW Mataram (Approval No: 062/ETIK/FKIP/III/2024), and all participants provided written informed consent.

Sample Size Justification: The sample size was considered adequate based on similar empirical studies using interactive multimedia tools with comparable sample sizes (e.g., Virtanen, 2018; Adiska & Musthapa, 2021). In exploratory intervention research, small sample sizes can provide valid insights into learning trends, especially when using within-subject pre-post comparisons.

Research Instruments

Conceptual Understanding Test

A 10-item essay test was developed to assess students' understanding of SN1 and SN2 reaction mechanisms. The items were designed based on conceptual indicators adapted from Treagust (1995) and Nakhleh (1993). The instrument was validated by two organic chemistry experts, resulting in a Content Validity Index (CVI) of 97.17% and a reliability coefficient (Cronbach's α) of 0.649. Note: Although the reliability score is acceptable, interpretation of test results must consider the open-ended, qualitative nature of some items, which may introduce scoring variability.

Student Perception Questionnaire

A 10-item Likert-scale questionnaire was used to assess students' perceptions of ChemTube3D, focusing on visual clarity, interactivity, usefulness, and motivation. The instrument was developed based on indicators from the Technology Acceptance Model (Davis, 1989) and Mayer's Multimedia Learning Theory (2009).

Instructional Procedure

The intervention consisted of five instructional sessions integrating ChemTube3D into classroom activities. The flow of the instructional intervention is outlined below.

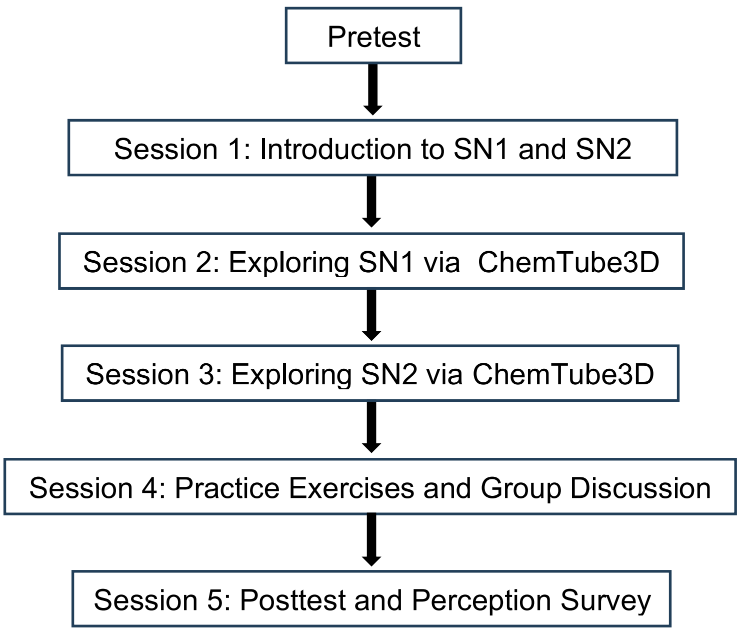

Figure 1. Instructional Intervention Flowchart

Data Analysis Techniques

Analysis of Learning Outcomes

The learning gains were analyzed using the following steps:

1. Students' pretest and posttest scores were calculated.
2. The Gain Score was obtained: Gain Score = Posttest−Pretest

3. The Normalized Gain (N-Gain) was calculated using Hake's (1998)
4. Each student's N-Gain score was classified into one of three categories.

Table 1. N-Gain Classification (Hake, 1998)

N-Gain Range	Category	Interpretation
≥ 0.70	High	Excellent learning gain
0.30–0.69	Medium	Moderate learning gain
< 0.30	Low	Minimal or ineffective learning gain

5. The N-Gain data were tabulated and visualized using distribution charts to identify patterns of conceptual improvement across the sample.

Analysis of Student Perception

Data from the perception questionnaire were analyzed using descriptive statistics:

1. Mean scores and frequency distributions were computed for each item.
2. Student responses were categorized (Strongly Agree to Strongly Disagree).

RESULTS AND DISCUSSION

Research Results

Students' Learning Outcomes

Learning outcomes were assessed using a conceptual essay test administered before and after the ChemTube3D-assisted instruction.

Table 2. Student Scores, Gain, and N-Gain Categories

No	Initials	Pretest	Posttest	Gain	N-Gain	Category
1	AN	20	68	48	0.60	Medium
2	RA	35	85	50	0.77	High
3	BS	30	70	40	0.57	Medium
4	TS	40	90	50	0.83	High
5	NA	25	75	50	0.67	Medium
6	MI	33	80	47	0.70	High
7	LI	28	72	44	0.61	Medium
8	RS	24	70	46	0.61	Medium
9	KA	31	78	47	0.68	Medium
10	AM	29	76	47	0.66	Medium
11	SN	38	88	50	0.81	High
12	AZ	22	69	47	0.60	Medium
13	DF	27	71	44	0.60	Medium
14	GL	26	68	42	0.57	Medium
15	YT	23	70	47	0.61	Medium
16	WN	34	83	49	0.74	High
17	DP	36	82	46	0.72	High
18	EP	20	65	45	0.56	Medium
19	KM	28	70	42	0.58	Medium
	Average	**26.76**	**70.97**	**44.21**	**0.66**	

The average pretest score was 26.76**,** which increased to 70.97 on the posttest, resulting in a mean gain of 44.21 and an average N-Gain of 0.66, categorized as medium.

N-Gain Distribution

Table 3. Distribution of N-Gain Categories

N	Pretest Mean	Posttest Mean	Gain Score	N-Gain	Category
19	26.76	70.97	44.21	0.66	Medium

Further analysis showed that:

- 6 students (31.6%) achieved a high N-Gain (≥ 0.70),
- 13 students (68.4%) were in the medium category (0.30–0.69),
- and 0 student (0%) fell into the low category (< 0.30).

Students' Perception of ChemTube3D

Students' perceptions were measured via a 10-item Likert-scale questionnaire. The average scores per indicator are presented in Table 3**.**

Table 4. Mean Perception Scores

No	Indicator	Mean
1	Visual clarity	3.6
2	Ease of use	3.5
3	Interactivity	3.7
4	Content relevance	3.4
5	Usefulness in SN1/SN2	3.8
6	Increased motivation	3.6
7	Support for self-study	3.5
8	Understanding mechanisms	3.7
9	Navigation simplicity	3.4
10	Overall satisfaction	3.6
Overall Mean		**3.58**

Discussion

The results of this study demonstrate that ChemTube3D significantly enhanced students' conceptual understanding of nucleophilic substitution reactions (SN1 and SN2), as reflected by a moderate normalized gain (N-Gain) score of 0.66. This finding indicates that 3D visualization tools play a critical role in supporting cognitive processing of dynamic molecular mechanisms, particularly in organic chemistry topics that involve complex electron movement, hybridization changes, and transition states. The improvement aligns with Mayer's (2009) Cognitive Theory of Multimedia Learning, which posits that learning is most effective when verbal and visual information are processed simultaneously (dual-channel processing). ChemTube3D facilitates this by integrating animated mechanisms with interactive 3D molecular representations, thereby reducing cognitive overload and supporting deeper mental model construction.

This finding is consistent with Bongers et al. (2020), who demonstrated that animated representations significantly improve students' mental models of organic reactions, especially for those with lower spatial ability. Similarly, Adiska & Musthapa (2021) found that 3D-based instruction on SN1 and SN2 reactions improved students' critical thinking and ability to link symbolic and submicroscopic representations. From a pedagogical perspective, ChemTube3D enables a more holistic application of Johnstone's triplet model (macroscopic, submicroscopic, and symbolic levels), a fundamental framework in chemistry education. As Vayakone (2024) emphasizes, bridging the gap between two-dimensional representations and three-dimensional spatial reasoning is essential for student comprehension, particularly in abstract topics like reaction mechanisms.

Further, Winstead & Huang (2019) reported that flipped classrooms incorporating ChemTube3D showed improved student engagement and performance compared to traditional lectures. In terms of student affect, Mistry (2019) found that 3D visualization reduced chemistry anxiety by increasing learners' confidence in tackling stereochemical and mechanistic problems.

However, the moderate level of improvement suggests implementation limitations. The short intervention period, limited prior experience with visual tools, and lack of guided navigation may have restricted deeper conceptual gains. As noted by Ferrell et al. (2019), digital visualization tools are most effective when embedded in scaffolded instruction and extended learning contexts such as labs and collaborative exercises.

Limitations and Future Research Directions

This study employed a one-group pretest-posttest design without a control group, limiting internal validity and generalizability. Additionally, although the conceptual test was expert-reviewed, its psychometric reliability was not statistically validated due to a limited pilot group. Future studies should employ quasi-experimental or randomized control trial designs, with larger and more diverse participant groups. Qualitative approaches such as student interviews, learning diaries, or think-aloud protocols are also recommended to explore how learners interpret and engage with dynamic visualizations. Moreover, it would be beneficial to examine long-term retention and transfer effects resulting from the integration of ChemTube3D in sustained instruction.

CONCLUSION

This study demonstrates that the integration of ChemTube3D as an instructional tool in organic chemistry specifically for teaching nucleophilic substitution reactions (SN1 and SN2) meaningfully enhances students' conceptual understanding. By leveraging interactive three-dimensional visualizations, students were not only able to improve their test scores but also found it easier to visualize complex reaction pathways, intermediates, and electron movement. The use of ChemTube3D contributed to the development of students' representational thinking, bridging the gap between symbolic representations and deeper conceptual comprehension. These findings underscore the importance of integrating multimedia-based technologies in chemistry education, particularly for abstract, mechanistic content, to promote active and constructive learning.

RECOMMENDATION

1. For instructors and educators, it is recommended to systematically incorporate interactive visualization tools like ChemTube3D into organic chemistry instruction to support students in grasping abstract and complex concepts more effectively.
2. For future researchers, it is advised to explore follow-up studies that examine long-term retention, spatial reasoning skills, and the comparative effectiveness of similar tools in hybrid or online learning environments.
3. Further research should also consider using a control-experimental group design and larger sample sizes to strengthen the generalizability of findings.

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