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STEREOCHEMISTRY BASED MULTIMODAL DIGITAL LEARNING TO IMPROVE SPATIAL ABILITY IN ISLAMIC HIGHER EDUCATION

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ABSTRACT

Spatial ability plays an important role in understanding stereochemistry; however, many students struggle with three-dimensional molecular structures and the associated energy changes. This study reconstructed a multimodal digital approach to stereochemistry learning and analyzed its effectiveness in improving students' spatial ability in Islamic higher education. The design and development (DDR) framework were systematically implemented through three phases: needs analysis (involving 117 respondents), design and development (including expert validation and a pilot trial with 32 representative users), and experimental evaluation (with a full cohort of 20 chemistry education students). The learning model incorporates computer-aided design, 3D printing, and computational software. During the needs analysis phase, the problems and requirements for the development of a stereochemistry course at the Islamic University were identified. A survey was administered to 117 pre-service teachers to explore perceptions toward new technologies, complemented by interviews and class observations. The design and development phase involved expert validation and an initial trial programme involving 32 chemistry education students at the university to assess practicability and usability. The evaluation phase tested the effectiveness of the learning model using a full cohort of the second-semester chemistry education department programme in one of the Islamic Universities. A pretest post-test control group design was employed to measure the effectiveness of the learning model in terms of spatial ability. The Mann–Whitney U test confirmed baseline equivalence ($U = 64.5$, $p = 0.259$). Post test scores showed a statistically significant difference (experimental: $M = 74.7$, $SD = 12.75$; control: $M = 54.5$, $SD = 20.18$; $t = 2.68$, $p = 0.017$) with a large effect size (Cohen's $d = 1.2$). The experimental group also achieved a higher normalized gain ($0.69 > 0.40$). These results indicate that the integrated digital and physical attributes in systematic learning design can enhance spatial ability.

KEYWORDS: Spatial Ability, Digital Technology, Higher Education.

1. INTRODUCTION

Spatial ability is essential for success in science, technology, engineering, and mathematics (STEM) disciplines (Coduto et al., 2024; Papakostas et al., 2021). Individuals with higher spatial ability can develop more accurate and schematic mental representations (Duffy et al., 2024) and perform well on tasks involving numerical representation (Li et al., 2025). Previous studies have shown that, compared with verbal or mathematical abilities alone, spatial ability is a key variable that specifically predicts success in STEM pathways (Wai et al., 2009). In chemistry learning, students are required to engage in spatial thinking because chemistry involves numerous molecular representations, reactions, and theoretical concepts, particularly in stereochemistry. Chemistry students must be able to visualize three-dimensional molecular structures based solely on two-dimensional representations or chemical formulas. In addition, students need to mentally manipulate molecular structures, such as rotating or comparing molecules in spatial arrangements, to understand molecular functions and intermolecular interactions. These spatial abilities are important for determining Newman conformations (Mistry et al., 2020) and molecular geometries (Rahmawati et al., 2021). All of these concepts require strong spatial abilities because they involve representational transformations of molecular structures in three-dimensional space (Elford et al., 2022; Ferk et al., 2003).

Stereochemistry is the study of the three-dimensional arrangement of atoms in molecules. To learn stereochemistry concepts, learners need to perform precise mental manipulations and spatial thinking (Wong et al., 2025). Failure to correctly visualize this transformation often leads to misconceptions (Wayan, 2015). Addressing these misconceptions is essential, especially for prospective teachers, as stereochemistry serves as a fundamental pillar in areas where molecular structure determines function. Its principles underpin drug design and development in pharmacy, where molecular configuration directly influences medicinal safety (Serrano-Ausejo & Mårell-Olsson, 2023), and also underpin the understanding of asymmetry, analysis, and purity in the sugar industry (Silva et al., 2020).

Despite the importance of spatial ability in stereochemistry learning, many students continue to experience difficulties in applying spatial reasoning when dealing with three-dimensional molecular structures (Echeverri-Jimenez & Oliver-Hoyo, 2021; Fernandes et al., 2021). Students often struggle to mentally rotate molecules (Salame & Kabir, 2022), shift viewpoints, and connect different molecular representations (Germain, 2025). Previous studies have attempted to involve digital technologies, including scientific visualization (Bogomolova et al., 2020), modeling (Bedewy et al., 2021), and simulation (Pushpalatha et al., 2023); however, they often rely solely on virtual representations without exploration of physical models. In contrast, students still require physical models when studying molecular spatial structures (Lee & Beggs, 2021). Several studies have indicated that physical models offer advantages for haptic perception, that is, the ability to understand through direct tactile experience (Nkosi & Mnguni, 2020). Computer-aided design (CAD) enables the creation of precise 3D models in a virtual environment, allowing users to manipulate objects from any perspective (Harron et al., 2022). 3D printing (additive manufacturing) extends this digital capability into the physical realm, producing tangible models that can be handled and examined (Martin et al., 2023).

Previous studies have explored the use of digital visualization tools, physical molecular models, and multimedia learning approaches to support stereochemistry learning. Digital tools, such as molecular visualization software and augmented reality, have been widely used to enhance conceptual understanding; however, these approaches often rely solely on virtual representations. In contrast, physical modeling using 3D-printed structures provides hands-on interaction but lacks dynamic computational features.

Digital technology provides a range of tools that can efficiently simulate energy levels without the need for complex hands-on laboratory work. Such an approach is not yet necessary for students in their early semesters. Chemistry software provides computational analysis of molecular properties, including energy minimization and conformational analysis, thereby linking spatial structure to thermodynamic stability (Mistry et al., 2020). Technologies such as computer-aided design (CAD) and additive manufacturing supported by 3D printing have enabled more interactive and data-driven approaches to representing complex structures. In particular, these technologies provide new opportunities for integrating digital computation with physical representation, allowing users to interact with abstract concepts in more tangible and dynamic ways (Kuťák et al., 2023).

Despite these advancements, the implementation of such technologies in learning environments is often fragmented. Many applications utilize individual tools, such as molecular visualization software or physical modelling, without integrating them into a unified system. To address these problems, this study proposes an integration of digital and physical molecular model that complement the Computer Aided Design (CAD), 3D printing technology, and computational software within a structured learning system. The proposed model combines digital technology (computational software and digital modelling) with tangible interaction.

2. LITERATUR REVIEW

It has long been believed that spatial ability is a key factor in an individual's success in learning scientific concepts and academic performance (Liu et al., 2021). For 40 years, researchers have investigated the relationship between spatial ability and achievement in chemistry learning (Herunata et al., 2025). Spatial ability is defined as the capacity to recall, reason about, and understand spatial relationships between objects and spaces (Antonucci-Durgan & Abramovich, 2024; Serrano-Ausejo & Mårell-Olsson, 2024).

Spatial ability is widely regarded as an essential cognitive skill, particularly in STEM fields. In its early development, it was described as the ability to solve problems involving the identification, estimation, and prediction of spatial relationships between objects (Li et al., 2025). Li et al., 2025). Over time, this concept has been refined and expanded by various scholars. McGee for example, distinguished two main components of spatial ability: spatial orientation and spatial visualization. Spatial visualization refers to the capacity to mentally manipulate objects, such as rotating or transforming them, while spatial orientation relates to understanding how elements are arranged and how they change when viewed from different perspectives (Bartlett & Camba, 2023).

Later frameworks further elaborated these dimensions. Lohman proposed three components: spatial visualization, spatial relations, and spatial orientation, whereas Linn and Petersen introduced a slightly different classification consisting of spatial perception, spatial visualization, and mental rotation. Building on these earlier models, Maier integrated the concepts into a more comprehensive five-factor framework, which includes spatial perception, spatial visualization, mental rotation, spatial relations, and spatial orientation. Together, these perspectives emphasize that spatial ability is not a single skill but a multidimensional construct that supports the mental representation and transformation of objects (Kveton et al., 2014).

Individuals with strong spatial abilities perform well in tasks that require the manipulation of two-dimensional and three-dimensional information, as well as the solving of visual-spatial problems (Cho & Suh, 2022). In the context of this study, three dimensions were selected as the primary focus: spatial orientation, spatial visualization, and spatial relations, following Lohman (1979). These dimensions were considered most relevant to stereochemistry learning and were used as the basis for developing the spatial ability instrument presented in Table 1.

Table I: Spatial Ability Dimension.

Spatial Ability Dimension	Description
Spatial orientation	The ability to imagine how an object looks from various perspectives by changing one's egocentric position.
Spatial Visualization	The ability to perform various spatial transformations that require moving or merging parts of a spatial image relative to others.
Spatial relation	Mental ability to rotate objects in a planar (two-dimensional) plane or outside the planar (three-dimensional) plane.

Previous studies have examined whether spatial ability can be improved by training using multisensory techniques and educational tools. Training that combines various sensors, such as auditory, visual, and tactile sensors, has been shown to improve spatial abilities. Research in cognitive science has shown that a person's ability to construct accurate internal representations can be enhanced through external representations (Eysenck & Keane, 2020a). External representations, in the context of chemistry, are concrete representations outside a person's mind that can be interacted with, such as handheld molecular models, computer images, and molecular sketches (Carlisle et al., 2015). This is in line with the Cognitive Theory of Multimedia Learning (CTML), which states that the use of more senses can improve the capture of new information into working memory (Mayer, 2024). The lack of integration between physical and virtual media limits the potential of technology-enhanced environments to support complex cognitive processes, such as spatial ability and structural interpretation. The integration of digital tools in the learning approach is called multimodal learning (Li Dong, 2025; Li & Dong, 2025). & Li & Dong, 2025).

In addition, the potential of combining computational software, digital modelling, and tangible models to support spatial ability development in the context of stereochemistry remains underexplored. Previous research often used individual computational tools or tangible models separately to learn stereochemistry.

3. METHODS

This study employed a design and development research (DDR) approach (Richey & Klein, 2014) to design, develop, and evaluate an integrated digital–physical learning model for stereochemistry. DDR is a systematic methodology widely used in computer science and educational technology research to develop and validate technology-based- systems through iterative phases of (1) needs analysis, (2) design and development, and (3) experimental evaluation (Padzil et al., 2021; Wuttiphan & Kwangmuang, 2025).

3.1. Need Analysis

The first phase aimed to identify the problems from actual workplaces (pre-service teachers at Islamic universities). A total of 117 pre service chemistry teachers, from 16 Islamic universities in Indonesia, participated in the survey. The survey was conducted by involving pre-service science teachers; the respondents came from Java, Sulawesi, and Sumatra Islands. The demographics of the participants are presented in Table II. The dimensions employed in the survey were adapted from Abdipour et al. (2024).

Table II: Demographic Aspects of Participants in Phase 1.

Demographic		Persentase
Gender	Male	12.8%
	Female	87.2%
Total		100%
University Type	Private	88.9%
	Public	11.1%
Total		100%
Region	Java Island	68.07%
	Sumatra Island	30.70%
	Sulawesi Island	1.30%
Total		100%

In addition, chemistry lecturers were interviewed, and curriculum documents (syllabi and course materials) were analyzed to identify gaps in existing instructional approaches. The instrument used in the study was a questionnaire consisting of several parts: the first part contained a brief introduction regarding the survey as well as a statement of agreement to fill out the questionnaire; the second part comprised questions in the form of demographic aspects containing questions regarding the background of the respondents; the third part contained questions regarding knowledge of digital technology in education computation software, 3D print technology, and computer-aided design; and the fourth part comprised questions related to the acceptance of new technology.

A semistructured- interview protocol was used to explore lecturers' perspectives on current challenges in teaching stereochemistry and the potential integration of multimodal digital technologies. Interviews and class observations were conducted to identify the problem in the actual context. The psychometric properties of the questionnaire on attitude new technology achieved the requirement of validity and reliability based on the Rasch Model, with *Cronbach's alpha* of 0.86 and average of item outfit MNSQ of 1.46 and item infit MNSQ of 0.82, *unidimensionality of raw variance explained by measure* at 77.5%.

Interview protocol was used to explore lecturers' and students' perspectives on current challenges in teaching stereochemistry and the potential integration of digital–physical technologies. Field notes and recordings were used to identify the problems in the classroom regarding stereochemistry learning at the Islamic University. The survey was administered online via Google Forms over two months-, while interviews were conducted individually with consent. Curriculum documents were systematically reviewed using an analysis checklist.

3.2. Design And Development

The second phase focused on designing the digital–physical learning model and developing its components, followed by expert validation and a pilot trial to assess its practicability and usability.

3.2.1. Design And Development

The learning framework (Figure 1) comprises three core technology components: (a) computer-aided design (for designing 3D molecular models), (b) 3D printing (for fabricating tangible molecular model kits with accurate proportions of angle and size), and (c) Chem3D (for computational energy analysis). These components are integrated through the *electronic stereochemistry flip book* (e-SFB), a digital e-book that serves as the central learning hub and contains tutorials, video guides, and interactive activities.

3.2.2. Expert Validation

The model was validated by five chemistry education experts. The experts assessed content accuracy, pedagogical appropriateness, technical usability, and model integration using a four-point Likert scale. The content validity index (S-CVI/Ave) across all aspects was 1.00, indicating high validity.

3.2.3. Pilot Trial

A pilot trial was conducted with 32 chemistry education students to assess the system's practicability and usability. The participants engaged with the full learning model, which consisted of 12 sessions, and completed a usability questionnaire.

3.3. Evaluation

The third phase evaluated the effectiveness of the integrated digital–physical learning model in improving spatial ability. A quasi experimental with a pretest–post-test control group design was employed (Creswell & Clark, 2011). The experimental group received instruction using the integrated digital–physical learning system, whereas the control group received conventional instruction using traditional methods with 2D static representations. Both groups were taught the same stereochemistry content over the same duration.

A full cohort of the 2024 semester chemistry education students at the Islamic University in Semarang participated in this phase. A total of 20 students were assigned to the experimental and control groups based on their existing class sections, maintaining the integrity of the instructional setting. The study extended over a one-year- period to strengthen the validity of the findings and account for potential temporal variability. A total sampling approach was used, and the cohort was organized into two intact classes by the department prior to the study. One class (N = 10) served as the experimental group, whereas the other class (N = 10) served as the control group.

Random assignment at the individual level was not feasible because the classes were pre-existing (intact groups) as scheduled by the university. To minimize selection bias, both groups were taught by the same instructor, followed the same course duration, and covered identical stereochemistry topics. The Mann–Whitney U test confirmed no significant difference in pretest spatial ability scores between the two groups (U = 64.5, p = 0.259), supporting baseline equivalence. Nevertheless, the use of intact classes may introduce confounding variables which are acknowledged as a limitation of this study.

Spatial ability was measured using a spatial ability test with the context of stereochemistry administered as a pretest and posttest. The instrument was adapted based on the spatial ability dimension, which consists of spatial orientation, spatial visualization, and spatial relations (Carlisle et al., 2015; Lohman, 1979 . Prior to implementation, the SAT was pilot-tested on 38 pre-service chemistry teachers. The pilot data were analyzed using Winsteps software based on the Rasch measurement model with the joint maximum likelihood estimation (JMLE) procedure, which converts raw dichotomous scores into interval-level logit measures (Linacre, 2024).

The logit scale enables both item difficulty and person ability to be located on the same continuum, allowing for a comprehensive evaluation of the instrument's psychometric quality. The SAT consisted of 15 items administered to 38 pre-service chemistry teachers. The results of the psychometric analysis are presented in Table III. Spatial Ability consisted of 15 items. As shown in Table III, the Rasch analysis indicated good overall model fit, with mean item infit and outfit MNSQ values close to 1. The item separation index (2.67) suggested that the instrument could distinguish multiple levels of item difficulty. Unidimensionality analysis showed that 41.8% of the raw variance was explained by the Rasch measure, with 14.0% unexplained variance in the first contrast. The instrument demonstrated acceptable reliability, with item reliability of 0.87, person reliability of 0.74, and Cronbach's alpha of 0.80. Overall, these results indicate that the instrument has adequate psychometric quality for measuring students' spatial ability.

Table III: The Summary of Rasch Parameters for Spatial Ability Test.

Psychometrics Attribute	Value

Number of Items	15
Mean	
item outfit MNSQ	1.06
item infit MNSQ	0.96
person outfit MNSQ	1.06
person infit MNSQ	0.98
Item separation	2.67
Unidimensionality	
Raw variance explained by measure	41.8%
Unexplained variance 1st contrast	14.0%

Both groups completed the spatial ability test prior to the intervention (pre-test). For the intervention, the experimental group engaged with the integrated learning system. The activities included CAD design, 3D printing, Chem3D analysis, and e-SFB guided activities, following the EMCPR syntax. During the engaging phase, students were introduced to contextual chemical phenomena to activate prior knowledge and stimulate inquiry. In the modelling phase, students explored molecular structures and rotations using tangible molecular models (products of CAD and 3D printing technology) and computational software to observe changes in molecular conformation and relative energy. After the scaffolding activities, students participated in problem-solving activities in which they worked collaboratively to investigate molecular conformations, manipulate bond angles, and analyze corresponding energy changes using computational software; subsequently, they shared their findings and engaged in class discussions to refine their understanding. The reflecting phase provided opportunities for feedback and reflection to consolidate spatial ability.

Data analysis involved a Mann–Whitney U test for the pretest results because the pretest data were not normally distributed. For the post-test, Welch's t-test was conducted (Minium et al., 1993) and Cohen's d was calculated to determine the effect size (Cohen et al., 2007). Prior to hypothesis testing, the normality of the data was examined using the Shapiro Wilk test. Improvement was further analyzed using normalized gain (N-gain) scores. All statistical analyses were conducted at a significance level of 0.05.

4. RESULTS AND DISCUSSION

4.1. Need Analysis Results

The needs analysis phase involved 117 pre-service chemistry teachers from 16 Islamic universities in Indonesia. The results provide an overview of participants' perceptions and readiness for the integration of multimodal digital technologies in stereochemistry learning. A total of 79.48% of respondents reported positive emotions regarding new technologies. This suggest that pre-service teacher at Islamic University has high readiness for the implementation of multimodal digital learning. The results are consistent with previous research which indicates that positive emotional dispositions, particularly optimism, can reduce resistance and ameliorate anxiety, thereby facilitating the adoption of emerging technologies (Ngwenya, 2025; Tyng et al., 2017).

Document analysis showed that current materials primarily rely on 2D static representations, with no integration of computational tools or physical models. This limitation contributes to the learning difficulties to learn stereochemistry and spatial ability. The following excerpt illustrates part of the interview transcripts collected during the preliminary field investigation.

Interviewer:
Bunga (pseudonym), based on the initial survey, you mentioned that organic chemistry is the most difficult course for you. Is that correct? May I ask the reason?

Bunga (pseudonym):
Yes, that is correct. I apologize, but sometimes I feel less motivated because the material is not tangible, the objects cannot be directly observed, yet we are required to analyze them with considerable effort. At times, I even question whether this knowledge will be useful in the future.

Interviewer:
What do you mean by "useful in the future"?

Bunga (pseudonym):
(Laughs) I do not mean to sound dismissive, but it often feels less relevant as it mainly involves manipulating formulas repeatedly.

Interviewer:
By "manipulating formulas," do you mean rotation of sigma bonds?

Bunga (pseudonym):
Yes, exactly. The rotations require us to draw and imagine structures from different viewpoints – sometimes placing the perspective behind and sometimes in front, which can be quite confusing for me.

Interviewer:
Arman, according to the initial survey, you also indicated that organic chemistry is the most difficult course. Is that correct? Could you explain why?

Arman (pseudonym):

It is not always difficult; however, I tend to struggle when identifying racemic mixtures from reaction mechanisms. After considering whether the attack occurs from the front or the back, I become uncertain about the orientation of the other groups and whether they remain upright or move in the opposite direction.

Based on these interview findings, it can be inferred that students encounter challenges in performing spatial transformations. These include mentally manipulating spatial representations, integrating or repositioning components of a structure relative to one another, and visualizing objects from various perspectives. In addition, a lack of motivation emerges when students perceive the subject matter as being abstract and disconnected from real-world applications.

4.2. Design And Development Results

Based on the results of the needs analysis in phase 1, the design and development phase aims to produce an integrated digital–physical learning system. This learning model consists of digital (computational software, computer-aided design) and physical components. Computer-aided design (CAD) refers to the use of computer-based tools to support the creation of tangible models using 3D printing technology. In learning systems, CAD has been shown to support not only the development of technical skills but also higher-order cognitive processes, such as critical thinking and problem solving (Feng & Wang, 2021). The integration of these components forms a coherent model that connects computational processing, digital modelling, and physical fabrication in a single workflow. The overall workflow of the proposed model is presented in Figure 1.

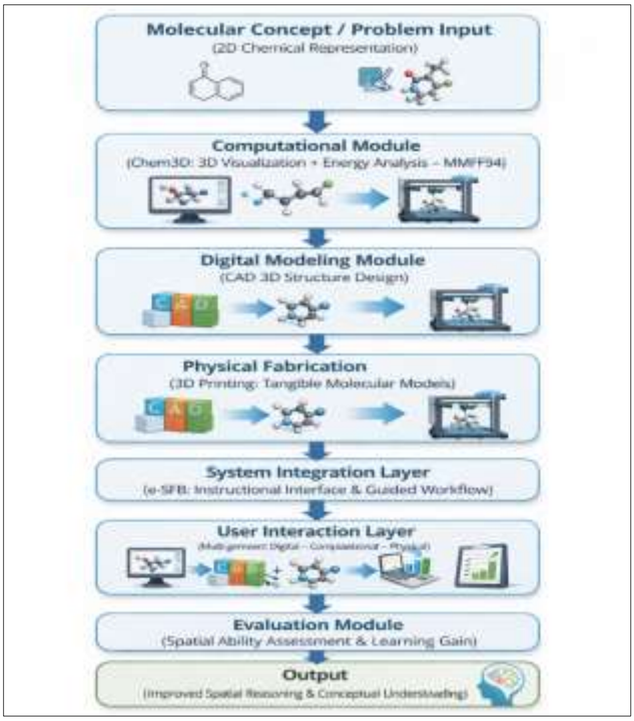

Figure 1: Workflow Of The Proposed Multimodal-Digital Learning Framework.

As illustrated in Figure. 1, computational software was integrated with physical three-dimensional molecular models through CAD, supported by 3D Print technology, enabling students to interact with molecular structures through both digital and tangible models. Such interactions require users to attend to spatial relationships among molecular components and perform precise mental transformations. In stereochemistry, this includes mentally rotating molecular structures to determine configurations (for example, R/S configurations) based on the *Cahn–Ingold–Prelog* rules (Carey, 2000).

Students engaged in spatially demanding learning tasks supported by both three-dimensional digital molecular manipulations using computational software and the construction of physical molecular models designed through computer-aided design and produced tangible model kits using 3D printing technology. Through these activities, students were able to interactively manipulate three-dimensional molecular structures and explore their space. From the perspective of the Cognitive Theory of Multimedia Learning (CTML), learning becomes more effective when information is presented through multiple sensory channels and meaningfully integrated with learners' prior knowledge (Mayer, 2024). This integration supports the construction of coherent mental models and facilitates the transfer of information into long-term memory, leading to more meaningful learning connections (Safari et al., 2021). This result aligns with previous research on cognitive training, which suggests that spatially oriented tasks can foster near-transfer effects on spatial abilities (Janavičiūtė-pužauskė et al., 2025).

Through computational molecular software and computer-aided design activities supported by 3D printing, students engaged in repeated spatial manipulation and object–object relational processing, which functioned as spatial training and supported the development of spatial ability. Previous studies have shown that the ability to construct accurate internal representations can be enhanced through sustained practice with external representations, such as diagrams, sketches, digital models, and physical models (Jones et al., 2021). Students conducted virtual experiments to generate molecular energy data using computational software (Figure 2) and used these data to evaluate molecular stability as part of the problem-solving process. By manipulating dihedral angles and observing the corresponding changes in molecular energy, students were able to distinguish between more and less stable conformations based on energy considerations rather than rote memorization.

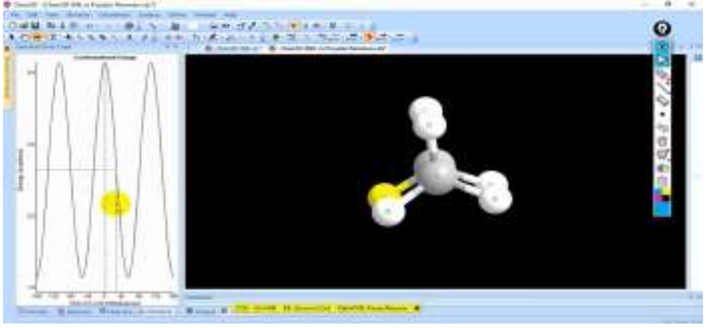

Figure 2: Example The Use Of Computational Software For Energy Analysis.

The learning activities provided with collaborative problem-solving experiences required exploration of molecular conformations and analysis of relative energy levels using computational chemistry software. For instance, through *the Trapped in the Alchemi Cave game* embedded in the electronic stereochemistry flip book (Figure 3), pre-service chemistry teachers were implicitly guided to engage in inquiry-oriented practices resembling scientific investigation.

Figure 3: Electronic Stereochemistry Flip Book (E-SFB).

Computational software (Figure 2) was integrated with physical three-dimensional molecular models, enabling students to interact with molecular structures through both digital and tangible representations (Figure 3 and 4) via eSFB. Such interactions required students to attend to the spatial relationships among molecular components and to perform precise mental transformations. In stereochemistry learning, students must mentally rotate molecular structures to determine R and S configurations by prioritizing substituents around the chiral carbon atom according to the Cahn–Ingold–Prelog rules (Carey, 2000; Eysenck & Keane, 2020b). Failure to correctly visualize these transformations often leads to incorrect configuration assignments (Solomon & Fryhle, 2011). The ability to imagine how an object appears from different viewpoints represents a key component of spatial ability, namely spatial orientation (Carlisle et al., 2015b; Harle & Towns, 2011).

Figure 4: Tangible Modelling Aid Fabricated From CAD And 3D Print.

The learning model was designed around the EMCPR instructional syntax, which consists of five steps: engaging, modelling, creating, presenting, and reflecting.

Table IV: The Learning Design Multimodal Digital Learning.

No	Phase	Description
1.	Engaging	Providing a phenomenon derived from Islamic values relevant to students' prior knowledge in order to facilitate the assimilation process within the cognitive structure. The Meaningful Learning Theory states that the process of knowledge occurs by linking pre-existing cognitive structures with new information, thereby making the new knowledge more durable in a person's cognitive structure (Mayer & Fiorella, 2022; Rockenbach et al., 2024).
2	Modelling	This phase facilitates the progressive differentiation process through meaningful learning. Concepts are refined by deepening the content and involving more general questions (phase 1); subsequently, more specific concepts are discussed (progressive differentiation) by deepening the material. For instance, the concepts of molecular conformation, Newman projections, and energy-level calculations for each conformation of compounds produced from crude oil are addressed. During the explanation, the lecturer assisted with concept visualization using Chem3D and Tangible Modeling Aids (TMAs).
3	Creating	Rockenbach et al., (2024) stated that cognitive conflict will occur after the progressive differentiation process. Therefore, to foster meaningful learning, a reconciliation process is necessary to ensure that the concepts taught are truly understood and incorporated into long-term memory. To provide students with opportunities for integrative reconciliation through new problem situations chosen based on their abilities, they can be invited to create new phenomena related to the topic being discussed. Students are asked to create mini projects using CAD and 3D printing.
4	Presenting	Based on cognitive engagement theory, participating in activities such as presentations can help students organize the information they have just learned systematically. Thinking with models requires an individual to construct and use mental models based on his or her personal knowledge and, sometimes, to think in 3D (Wang, 2007).
5	Reflecting	Sweller's cognitive load theory states that feedback plays a crucial role because it can help reduce cognitive load by providing guidance and explanations that help learners process information effectively and efficiently (De Jong, 2010). The process of synthesizing information and building connections between concepts is believed to strengthen retention in a learner's cognitive structure (Ausubel, 2003).

The learning model was then validated by experts. Experts assessed the system based on four aspects: functionality, usability, workflow, and digital technology integration. Content validity was evaluated using the Item-Level- Content Validity Index (I-CVI) and the Scale-Level- Content Validity Index (S-CVI/Ave). An I-CVI value of 1.00 indicates perfect agreement among experts, whereas an S-CVI/Ave value above 0.90 is considered excellent (Saiful & Yusoff, 2019). As shown in Table V, all four aspects achieved experts' agreement (EA) mean score= 5.00 with I-CVI = 1.00 and S-CVI/Ave = 1.00, indicating that the learning model met the content validity.

Table V: Expert Validation Results.

Aspect	EA	I-CVI	S-CVI/Ave
Functionality	5	1.00	1.00
Usability	5	1.00	1.00
Digital Technology	5	1.00	1.00
Learning Design	5	1.00	1.00

These results confirm that the integrated digital–physical learning model meets content validity requirements and is suitable for implementation in the next phase. Following expert validation, an initial trial (pilot trial) was conducted to assess the practicability and usability of the integrated digital–physical learning model in an authentic learning environment. The purpose of this phase was to identify any technical issues, clarify instructional procedures, and gather preliminary feedback from representative users prior to full experimental evaluation. During the first session, the users utilized Blender, a comprehensive 3D modelling software for CAD activities. However, several students reported technical difficulties, noting that Blender was resource-intensive and caused performance issues on their laptops. The users expressed a preference for a web-based solution that would not require software installation.

In response to this feedback, the CAD component was replaced with Tinkercad, a browser-based, user-friendly CAD platform that requires no installation and runs smoothly on standard laptops. Tinkercad was selected because it retains the essential 3D design capabilities needed for molecular modeling while significantly reducing technical barriers. The tutorials were revised accordingly to align with Tinkercad's interface and workflow.

After the revision, participants completed a usability questionnaire consisting of 15 items rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The mean usability score was 4.2 out of 5, indicating that the revised model was well-received and considered easy to use. Students reported that Tinkercad was much more accessible and allowed them to focus on the learning objectives rather than struggling with software installation and navigation. Open-ended responses indicated that the CAD tutorials and the e-SFB navigation were particularly helpful. The mean usability score was 4.2 out of 5, indicating that the model was well-received- and easy to use.

Recent findings in neuroscience suggest that mental imagery involving tactile stimulation activates multiple brain regions, including the primary somatosensory cortex, which is responsible for processing touch-related information (Nierhaus et al., 2023). In line with this, a researcher reported that tactile-supported visualization tools can facilitate molecular rotation processes, thereby engaging the visuospatial sketchpad, a component of working memory responsible for storing and manipulating spatial information (Teng, 2022).

Previous studies have demonstrated the effectiveness of physical models in supporting chemistry learning. One study utilized tactile visualization tools to explain intermolecular forces in organic chemistry (Lee & Beggs, 2021), whereas another study employed physical materials, such as jelly and clay, to improve visuo-semiotic reasoning skills (Nkosi & Mnguni, 2020). These findings highlight the importance of tactile interaction in supporting spatial reasoning and conceptual understanding. Within learning contexts, the incorporation of tactile interaction has been shown to enhance multimodal engagement and improve learners' ability to understand abstract concepts by making them more concrete and accessible (Boistrup & Selander, 2021). However, despite the advantages of tactile models, physical representations alone are insufficient for supporting higher-level analysis in stereochemistry. In particular, understanding molecular stability requires the ability to analyze energy levels and conformational changes, which cannot be directly observed through static physical models.

To address this limitation, computational chemistry tools are required to simulate molecular behavior, including energy minimization and conformational analysis (Kokic et al., 2024). This indicates the need for an integrated approach that combines physical interactions with computational analysis. Based on these considerations, the proposed learning model integrates two complementary technological components: computational molecular software and computer-aided design supported by 3D printing technology. The model enables learners to visualize molecular structures digitally, perform computational analyses of molecular energy, and interact with tangible molecular models produced through additive manufacturing.

A tangible modelling aid (TMA) was developed as a physical molecular kit derived from computer-aided design (CAD) and fabricated using 3D printing technology. This process follows the principle of additive manufacturing, in which objects are constructed layer by layer using materials such as polylactic acid (PLA). The physical models provide tactile feedback, whereas computational tools (Chem3D) support energy analysis, thereby enabling a more comprehensive understanding of stereochemical structures.

4.3. Experimental Evaluation Phase

The final phase of DDR is to evaluate the effectiveness of a digital-physical learning system. This phase wants to answer research question, namely: (i) does the learning model effective in enhancing the spatial ability of chemistry education students in university? (ii) What is the impact of the digital-physical learning model on the spatial ability of pre-service chemistry teachers?

To answer this research question, a pretest–post-test control group design was used to test the effectiveness of the developed digital–physical learning model. A pretest–post-test control group design was employed in this study because it is appropriate for examining the effects of interventions in real-world classroom settings (Creswell & Guetterman, 2019). The instructional intervention involved a digital–physical stereochemistry learning model that integrated chemistry software for molecular energy analysis (Chem3D) and computer-aided design (CAD) using *TinkerCAD* to design and fabricate three-dimensional (3D) molecular models. All digital tools and activities were organized in an electronic stereochemistry flip book (e-SFB) to facilitate instructional coherence and ease of use. The control group received conventional expository instruction supported by static visual presentations delivered through PowerPoint slides. To ensure that treatment affected student spatial ability, pretests were administered to both groups as a baseline to demonstrate that both groups had similar spatial abilities. Subsequently, a post-test was administered after treatment, and the difference between the pretest and post-test scores indicated whether there was a measurable effect after treatment.

Spatial ability is essential for success in science, technology, engineering, and mathematics (STEM) disciplines (Coduto et al., 2024; Papakostas et al., 2021). Students must mentally manipulate molecular structures, such as rotating or comparing them, to understand molecular functions and intermolecular interactions. These spatial abilities are important for determining Newman conformations (Mistry et al., 2020) and molecular geometries (Rahmawati et al., 2021). All these concepts require strong spatial abilities because they involve representational transformations of molecular structures in three-dimensional space (Elford et al., 2022; Ferk et al., 2003).

The pedagogical framework offers varied representations of opportunities for spatial training, thereby creating more accessible and cognitively stimulating environments for mastering complex subjects. Moreover, empirical research on integrated digital–physical learning models that simultaneously incorporate multiple representations, interactive manipulation, and tangible elements remains limited. Therefore, this study aimed to investigate whether there is a significant difference in spatial ability between pre-service chemistry teachers who experience multimodal digital stereochemistry learning and those who receive conventional static representation instruction.

The preliminary analysis of the pretest scores aimed to determine the baseline equivalence of the control and experimental groups. Table VI shows that there were no significant differences between the control and experimental groups in terms of pretest scores (U = 64.5, p = 0.259). This result indicates that the two groups had equivalent initial ability levels.

Table VI: Results Normality and Group Difference of Pre-Test.

Group	Mean (SD)	p-value	Mann–Whitney U	p value
Control	25.3 (9.06)	0.012	64.5	0.259
Experimental	20.9 (8.12)	0.040		

After the intervention, both the experimental and control groups received the post test. The Shapiro–Wilk normality test indicated that the post-test spatial ability scores of both the experimental group (W = 0.88, p = 0.127) and the control group (W = 0.90, p = 0.230) were normally distributed. Therefore, a parametric statistical analysis was applied to compare the post-test scores between the two groups. As shown in Table VII, the t-test of post-test showed a statistically significant difference in spatial ability scores between the experimental and control groups. The experimental group achieved a higher mean score (M = 74.7, SD = 12.75) than the control group (M = 54.5, SD = 20.18), t= 2.68, p = 0.017.

Table VII: T-Test Results.

Group	Mean (SD)	t *(df)*	p Value	Cohen’s d Value
Experimental	74.7 (12.75)	2.68 (15.20)	0.017	1.2
Control	54.5 (20.18)			

The large effect size of the intervention is indicated by Cohen’s d = 1.2 (Table VII). Further analysis using normalized gain (N-gain) scores also showed that the experimental group achieved a higher mean score of N-gain (0.69) than the control group (0.40), indicating greater learning improvement among students who experienced the digital–physical learning system. This improvement in the experimental group can be attributed to the students' engagement in spatially demanding learning tasks supported by both three-dimensional digital molecular manipulations using computational software and the construction of physical molecular models designed through computer-aided design and produced as tangible model kits using 3D printing technology. Through these activities, students were able to interactively manipulate three-dimensional molecular structures and explore their space. This finding is consistent with the prior research that providing students with repeated opportunities to construct and manipulate external representations, such environments support spatial ability development by reducing cognitive load by offloading information from working memory and strengthening visualization processes (Atit et al., 2020; Olimpo, 2013).

Such interactions encouraged students to attend to spatial relationships among molecular components rather than relying on static two-dimensional representations typically found in paper-based texts. From the perspective of the *Cognitive Theory of Multimedia Learning* (CTML), learning becomes more effective when information is presented through multiple sensory channels and meaningfully integrated with learners' prior knowledge (Mayer, 2024). This integration supports the construction of coherent mental models and facilitates the transfer of information into long-term memory, leading to more meaningful learning connections (Safari et al., 2021). This result aligns with previous research on cognitive training, which suggests that spatially oriented tasks can foster near-transfer effects on spatial abilities (Janavičiūtė-pužauskė et al., 2025).

Through computational molecular software and computer-aided design activities supported by 3D printing, students engaged in repeated spatial manipulation and object–object relational processing, which functioned as spatial training and supported the development of spatial ability. Previous studies have shown that the ability to construct accurate internal representations can be enhanced through sustained practice with external representations, such as diagrams, sketches, digital models, and physical models (Jones et al., 2021).

Although the experimental evaluation was conducted over a one-year- period to strengthen validity and a total sampling with a full cohort was used, the sample size remained limited (N = 20). Future research should replicate the study with larger and more diverse samples across multiple institutions to enhance the generalizability of the findings. Multi-site studies would also allow the examination of contextual factors that may influence the effectiveness of the system.

5. LIMITATIONS

While the sample size is modest, the study employed a full cohort design with total sampling over one academic year, which reflects the actual class size in this Islamic higher education context. Furthermore, the large effect size (*Cohen's d* = 1.2) indicates that the observed difference is substantively meaningful despite the small sample. Additionally, this study followed the DDR framework, where the experimental phase prioritizes internal validity and in-depth testing of the developed model rather than broad generalizability at this stage.

6. CONCLUSION AND RECOMENDATION

Content validity was confirmed through an expert review (SCVI/Ave = 1.00), and its practicability was established through iterative refinement. The experimental evaluation further validated the effectiveness of the learning system, showing a statistically significant improvement in spatial ability *($t = 2.68$, $p = 0.017$)* with a large effect size (Cohen's d = 1.2). These results indicate that the integrated model effectively supports spatial ability. This study contributes a validated learning model that uniquely combines three digital technologies–computer-aided design (CAD), 3D printing (additive manufacturing), and computational software–within a coherent learning design that unifies digital modelling, physical fabrication, and molecular energy analysis. This learning model can be adapted to other scientific domains that require spatial visualization and multi-representational understanding. The study also validates the good psychometric properties of the spatial ability instrument in the context of three-dimensional molecular aspects. Further research with a larger sample size is strongly recommended to ensure wider applicability.

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