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A Cognitive Load Approach to Molecular Geometries: Augmented Reality Technology and Visuospatial Abilities in Chemistry

Conor Desmond Kenneally and Brendan Bentley *

School of Education, University of Adelaide, Adelaide 5005, Australia; conor.kenneally@adelaide.edu.au
* Correspondence: brendan.bentley@adelaide.edu.au

Abstract: Within chemistry education, methods for effectively teaching students the three-dimensional spatial arrangements of matter at the molecular level remains a topical issue. As a form of geometric problem solving, it requires learners to apply mental rotation abilities as an evolved visuospatial skill to obtain subject-specific content knowledge. Recent research into the use of Cognitive Load Theory (CLT) as a framework for instructional design in conjunction with augmented reality (AR) technology as a learning tool has begun to show promise in reducing unnecessary cognitive activity to improve learning. Yet, broader conclusions remain inconclusive, especially within the context of a learner's mental rotation abilities. This study investigated the relationship between these factors by collecting data using a 2 × 3 experimental design that divided a sample of Year 10 students (n = 42) into two groups. The intervention group (n = 24) used mobile devices utilising AR technology with instructional 3D molecular geometry content featuring design principles based on CLT to encourage hand movements to rotate three-dimensional molecular structures. The non-AR-based control group (n = 18) was taught using traditional methods. Analysis of the data revealed participants using AR technology that featured CLT design principles experienced less cognitive load and improved achievement in post-testing compared to those taught using traditional methods, suggesting under certain conditions, the use of hand movement applied to AR design material improves learning.

Keywords: cognitive load theory; augmented reality; mental rotations; molecular geometry

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1. Introduction

Human cognition, similar to other physiological traits, can be understood as a result of evolutionary processes, driven by natural selection to improve survival and reproductive fitness [1]. The evolution of innate cognitive knowledge that is essential to survival is known within the discipline of evolutionary educational psychology as biological primary knowledge [2]. Yet, the modern world requires the learning of much more complex and abstract culturally specific biological secondary knowledge. This is knowledge that lacks the same evolutionary impetus and requires conscious effort often facilitated by educational institutions [3]. Cognitive Load Theory (CLT) utilises this understanding of evolved human cognitive processes to develop a theory of instructional design underpinned by these evolutionary implications for human learning [4]. CLT informs the manner in which schemas are acquired and transferred from a learner's working memory (WM) to their long-term memory (LTM) during complex cognitive tasks [5]. The WM's capacity and duration plays a pivotal role in the efficacy of this process. When the WM's limited capacity is overloaded and the available cognitive resources exceed the WM's maximum cognitive capacity, the efficiency of schema transfer is inhibited and meaningful learning is prevented [6].

Within the context of educational institutions, the teaching of chemistry as a biological secondary knowledge is a subject that imposes high WM demands. Its challenge is somewhat unique amongst other subjects due to the multiple levels of representation and interrelating levels of thought inherent to its content, requiring a learner to consider phenomena between macro, sub-micro, and representational levels of representation [7]. As such, cognitive limitations can quickly be exceeded through the restrictions of WM demands when a learner is expected to process such a volume of information [8]. Recent advances in the use of augmented reality (AR) technology to aid mental rotation and to reduce cognitive load and improve student-learning outcomes in chemistry have shown promise. AR technology involves imposing computer-generated virtual images onto a real environment, most often via an application utilising a phone's camera [9]. Within the context of the chemistry classroom and studying molecular geometries, a number of studies have suggested its benefit for optimising learner cognitive load by imposing cognitive load effects [10–12]. By substituting virtual objects onto real environments, AR technology can assist in directing and guiding the learner by using visual triggers and geographical information [13] to potentially reduce the number of elements required for processing by the WM.

The effect of AR technology to enhance the mental rotation ability of secondary chemistry students studying molecular geometries and the perceived task difficulty of utilising AR sympathetic technology to reduce cognitive load remains unresolved, with only a limited amount of research having been undertaken into this relationship [11]. By investigating how the implementation of this technology within an educational context can be optimised, a potential barrier to achievement in chemistry could be reduced [14]. This paper seeks to inform the current field of study by interrogating the following research question: What effect does AR technology with molecular geometric content designed using CLT have on secondary-science students' mental rotation abilities? Two further questions were also posed: What effect does mental rotation ability have on cognitive load? And can cognitive load and achievement be altered using AR technology when students engage in mental rotation?

1.1. Cognitive Load Theory and Visuospatial Abilities

Both the LTM and WM are considered essential characteristics of human cognitive architecture and fundamental to the acquisition of schemas. The LTM, as an information processing system, is elementary in determining the bulk of all human cognitive activity, highlighting its tremendous potential for total capacity [15]. In contrast, the WM is much more restricted in the amount of information that it can process at any given time, yet remains the main structure responsible for processing new information [16]. While the WM is limited when dealing with novel information, it is essentially limitless when dealing with biological secondary knowledge once it exists in the LTM [17]. Novel information that is to be acquired requires the WM to allocate significant resources to process and transfer information to the LTM. If the processing and transfer of the novel information exceeds the WM capacity, the WM will be overloaded and hinder effective learning [18]. As learners develop and increase their pre-existing cognitive schemas, the number of elements are able to be chunked and treated as one unit, as opposed to many singular or separate elements [19]. CLT provides the conceptual framework to design instructional procedures to reduce WM load and to enable domain-specific schemas to be more efficiently transferred to the LTM, allowing learners to function more effectively in a particular learning environment [20].

The adaptation of the human eye enables the WM to process and transfer visuospatial information to the LTM and takes advantage of both the WM and LTM functions. The transfer of visuospatial information from the WM that is to be retained by the LTM is the cognitive process of spatial learning, a crucial skill integral to the species survival and reproduction [21]. The evolution of the human brain has enabled the capacity for visuospatial processing, a cognitive process defined as the WM's ability to generate and transform visual and spatial information [22]. Geary and Berch [2] describe this visuospatial processing as a type of biological primary knowledge where different visuospatial abilities are responsible for controlling a diverse range of cognitive abilities [3]. Mental rotation is considered as a specific type of visuospatial skill that involves the ability to transform an object by moving it through an imagined space, an ability that can be determined by how accurately and rapidly one is able to mentally move an object, e.g., by rotating it [23]. Whilst visuospatial abilities embody biological primary knowledge, much variation can still be observed in ability levels within a population [14]. Mental rotation, specifically, has been observed as particularly variable between individuals [24]. Yet, research suggests visuospatial ability is able to be influenced positively by educational interventions, implying the potential malleability that it has as a skill [25].

1.2. Mental Rotation and Molecular Geometries

Many aspects of content taught in modern educational institutions, such as geometric problem solving, require the processing of visuospatial information through mental rotation [26]. Geometric problems require learners to perform transformations of objects in order to analyse both the shape and orientation of 3D objects, in addition to translating this understanding between 2D and 3D representations [27]. The consequence of this is a high correlation between a learner's mental rotation ability level and achievement in mathematics being readily observed [28]. Processing complex mental rotation problems requires a learner to store, maintain, and interpret complex representations of visuospatial information using the limited resources of the visuospatial sketchpad, a feat less likely to overload those who have higher spatial ability capacity [29]. Chemistry, as the study of matter and how matter interacts, requires the navigation and manipulation of molecular geometries on a scale both unobservable and difficult to interact directly with. Mental rotation skills permeate numerous topics within a chemistry curriculum at all levels, requiring learners to use 2D diagrams to interpret 3D spatial arrangements [30]. As with geometry, a student's ability to understand and manipulate these 3D structures is influenced by their mental rotation visuospatial ability [11], ultimately inferring their ability to learn from visual representations [31].

1.3. Working Memory and Executive Function

The function of the WM to deal with mental rotation activity associated with 3D chemical structures can be optimised utilising CLT principles [16]. The WM can be considered to comprise of two levels of functioning composed of three components: a higher level consisting of a central executive structure responsible for controlling two lower-level storage components, the phonological loop, and the visuospatial sketchpad (refer to Figure 1) [3].

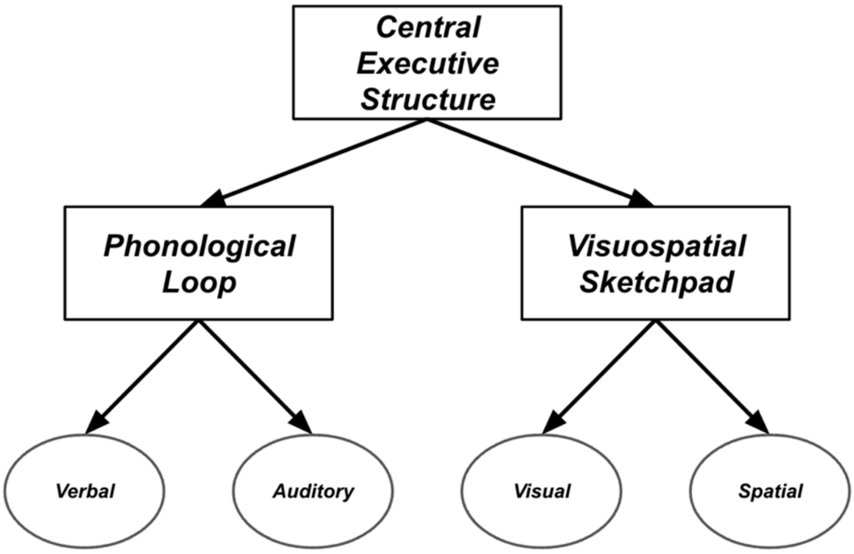


Figure 1. Components of WM.

Each component is responsible for processing differing types of information, with the phonological loop responsible for processing verbal and auditory information, whereas the visuospatial sketchpad is responsible for processing visual and spatial information [3]. The cognitive theory of multimedia learning (CTML) considers multiple representations of external information. The processing of dual and multiple information can be explained through dual coding theory, wherein the construction of meaning and knowledge through modality-specific mental representations arises from the two systems [32]. The effect of multiple sources of information requiring simultaneous processing by the limited resources available to the WM impacts the efficiency of schema transfer from the WM to the LTM and, thus, problem-solving capacity. To alleviate the limitations of the WM capacity and maximise visuospatial processing, Castro-Alonso, Ayres, and Sweller [16] propose that CLT and CTML principles can be utilised to optimise the visuospatial processing of the learner by guiding task design to reduce any unnecessary visuospatial processing a learner needs to perform. The adoption of CLT and CTML principles to improve visuospatial processing is, in part, supported by the malleability associated with spatial abilities and the potential that educational intervention can have in improving these types of skills [25], where one type of spatial skill can additionally transfer improvement to another type of spatial skill [33].

1.4. Augmented Reality Technology and Cognitive Load Effects

AR technology has been identified as an emerging technology exhibiting promising results in improving visuospatial processing by reducing unnecessary cognitive activity [11,34,35]. Within the context of studying molecular chemistry in the classroom, a number of studies have suggested AR may benefit learning by adopting CLT principles [10,12] through its imposition of computer-generated virtual images onto a real environment [9]. It is suggested that AR technology can assist in directing and guiding a learner's visual trigger and geographical information [13] and can signal important geospatial information to assist visuospatial processing to understand and visualise abstract concepts and complex spatial relationships [35]. The application of AR to recall or support the triggering of past schemas can enable the chunking together of separate elements so they can be treated as one singular unit, known as the signalling principle. This strategy encourages the reduction of cognitive load and can counter the effects of element interactivity by incorporating visual cues that signal only essential learning elements [36], reducing the amount of novel information in the visuospatial processor to optimise the visualisation process [22]. Comparable studies have rationalised AR's potential to promote a lower investment of cognitive effort required when manipulating molecular geometries by reducing the demands on visuospatial processing [11].

Instructional research involving human movements has also demonstrated the effectiveness of using hand gestures and object manipulation to facilitate learning across various subjects [37–39]. Researchers have found gesturing and object manipulation to benefit tasks such as solving math problems [40] and understanding complex science concepts [38], with De Koning and Tabbers [41] providing a comprehensive review further supporting the positive impact that these instructional approaches can have. While it is suggested actions such as gesturing and tracing have origins in biological primary knowledge, when they are applied to learning biological secondary knowledge, these types of actions may support cognition to positively influence a learner's experienced level of cognitive load [42,43]. AR-based learning readily embodies forms of gesturing and tracing by using hand gestures and body movements associated with the human movement effect. The effect suggests that certain movements used to support learning are automated and, therefore, have little impact on the use of the WM's resources. The technology adopts gesturing and tracing by using hand gestures and body movements to create and modify 3D digital structures, allowing the creation and manipulation of molecular geometries [10]. The success of gesturing and tracing on academic achievement within the context of visuospatial processing has been demonstrated to correspond with a learner's existing visuospatial ability levels, with research suggesting its potential to be particularly effective in improving learning outcomes for lower visuospatial-ability learners [44].

Whilst some evidence exists suggesting the potential for AR technology to reduce the cognitive load demands of visuospatial processing during geometric manipulation by improving conceptual understanding through enhancing visualisation [45], broader conclusions remain inconsistent [36]. Some technology has been shown to have no significant effects in reducing cognitive load when implementing AR in the learning of molecular geometries, with certain cases suggesting it may actively be hindering the process [36,46,47]. Although some literature has explored the use of AR as a classroom tool to instruct molecular geometries, further research is required to strengthen and clarify the conclusions that can be drawn regarding its effectiveness as a learning tool. To further inform the field of study, additional research is required to better understand the effect optimised CLT science visualisations have on visuospatial processing skills, particularly in relation to the signalling principle [16]. This study aimed to achieve this by investigating the relationship between cognitive load and achievement in post-testing when utilising an AR-based learning intervention to support student mental rotation abilities in understanding three-dimensional molecular structure.

2. Method

2.1. Participants and Procedure

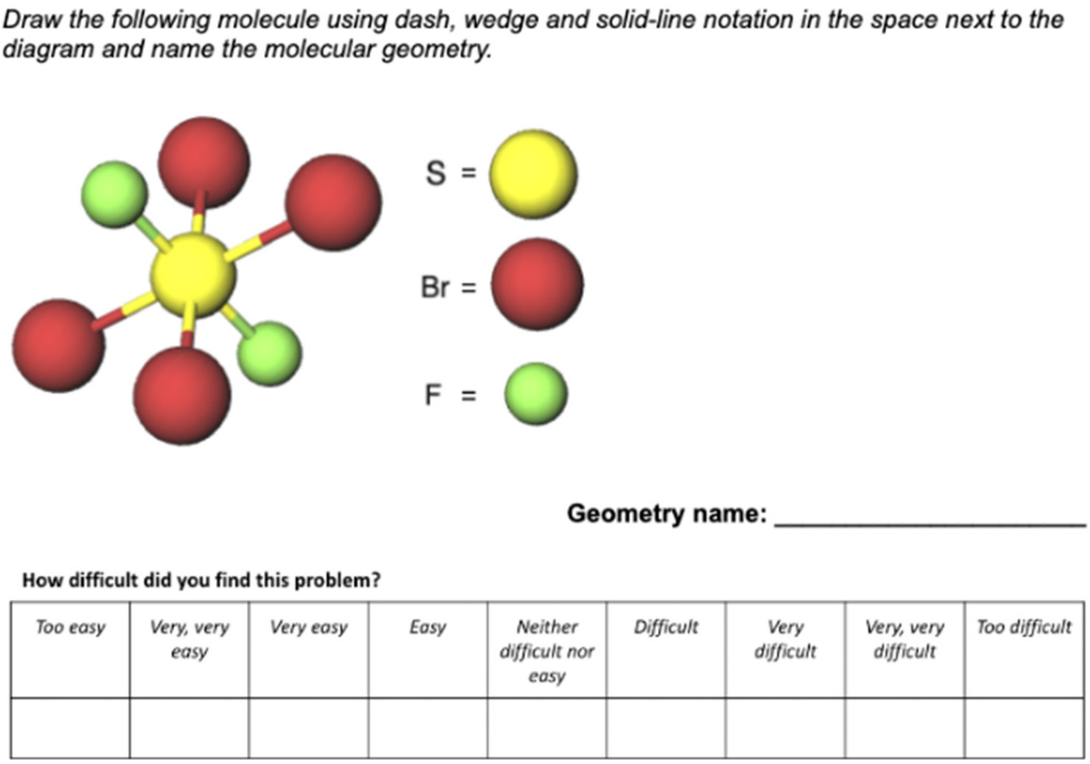
This study was conducted with an original group of 49 Year 10 (15- to 16-year-old) students from an independent Australian secondary school. The number of participants was reduced to 42 due to student non-attendance during the post-testing phase of the study. A 2 × 3 experimental method was used, with participants randomly placed into the non-AR control (C) group ($n = 18$) and AR-based intervention (I) group ($n = 24$). Both groups received 45 min instruction during a classroom lesson wherein the C group was provided with traditional teaching methods and the I group received instruction that utilised AR technology. Achievement and corresponding cognitive load data were collected at three times: pre-test (T1), immediate post-test (T3), and delayed post-test (T4). T3 data were collected one day after treatment, and T4 data were collected seven days after treatment (refer to Table 1). The 45 min classroom lesson (T2) was implemented after the pre-testing and was dedicated solely to the delivery of content; no data were collected during this session. All sessions with the I and C groups were conducted separately from each other, taking place at different times. Each session was undertaken between August and September 2023 and was implemented independently of participants' schooling. Ethical guidelines and regulations were carefully considered to ensure the safety and feasibility of participants, with ethical clearance being granted by the University of Adelaide (approval number: H-2023-086). Participation was voluntary, with informed consent collected from both the participants and their guardians.

Table 1. Experimental methodology.

Group	**T1 Pre-Test**	**T2 Classroom Lesson**	**T3 Immediate Post-Test**	**T4 Delayed Post-Test**
Intervention (I)	6 content questions	Lesson taught using booklet with digital AR prompts accompanying molecular geometries	6 isomorphic content questions	6 isomorphic content questions
Control (C)	6 content questions	Lesson taught using booklet with diagrams accompanying molecular geometries	6 isomorphic content questions	6 isomorphic content questions

2.2. Materials

The pre-test assessed participants' prior content knowledge and associated levels of cognitive load. The six test questions were contained in a test booklet, with each participant given 10 min to complete the test for a total of 14 marks. The pre-test collected participants' baseline prior knowledge and cognitive load data. Cognitive load was measured using self-reporting methods by participants responding to the perceived difficulty based on a 9-point Likert scale from 'too easy' to 'too difficult' (refer to Figure 2). Utilising subjective measures of task difficulty via Likert scales has been extensively demonstrated to be a reliable and valid method [48], especially for implementation with more complex tasks [49]. This approach has also had its effectiveness demonstrated in similar studies regarding the relationship between CL and achievement when implementing AR technologies into the study of geometric principles in chemistry comparable to this study [11,50,51]. The two post-tests were designed with isomorphic questions being incorporated in the content section of the pre-test, again with each question accompanying the prompt to measure cognitive load.



Draw the following molecule using dash, wedge and solid-line notation in the space next to the diagram and name the molecular geometry.

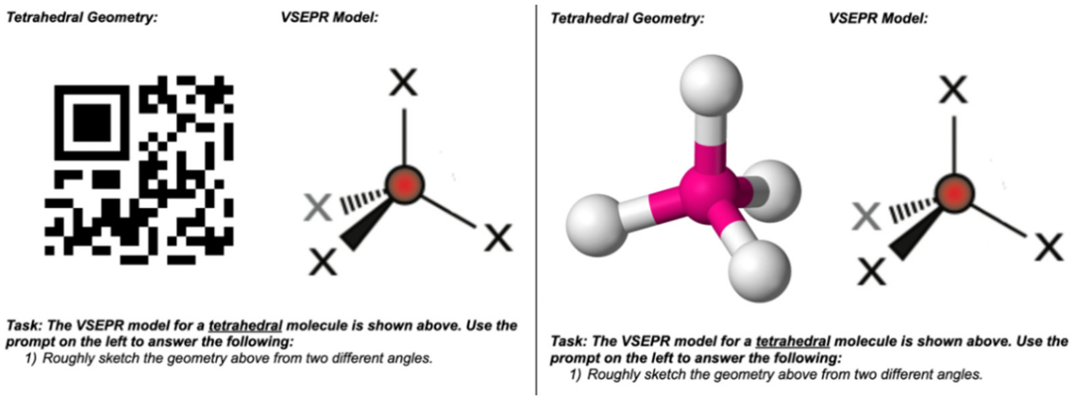
Geometry name: ______________________

How difficult did you find this problem?

Too easy	*Very, very easy*	*Very easy*	*Easy*	*Neither difficult nor easy*	*Difficult*	*Very difficult*	*Very, very difficult*	*Too difficult*

Figure 2. Example of content question and cognitive load measurement from the pre-test.

A treatment lesson at T2 was undertaken based on molecular geometric and Valence Shell Electron Pair Repulsion (VSEPR) theory content. Identical booklets were provided to the I and C groups differing only in the inclusion or exclusion of an AR digital prompt that accompanied the VSEPR model of the molecular geometry. The digital prompt was to be used with an app downloaded onto each participant's mobile device to generate an interactive 3D model of the molecular geometry. In lieu of the digital prompt, the C group was instead given diagrams typical of that which would accompany this content in a more traditional lesson or textbook (refer to Figure 3). Teacher instruction given during the teaching aspect of the class was controlled by utilising the same lesson slides during both sessions.



Tetrahedral Geometry: **VSEPR Model:**

Task: The VSEPR model for a tetrahedral molecule is shown above. Use the prompt on the left to answer the following:

1) Roughly sketch the geometry above from two different angles.

Tetrahedral Geometry: **VSEPR Model:**

Task: The VSEPR model for a tetrahedral molecule is shown above. Use the prompt on the left to answer the following:

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Figure 3. Example question from T2 lesson booklets illustrating the use of the AR digital prompt for the I group (on the **left**) compared with the diagram provided for the C group (on the **right**).

The MoleculAR App

A mobile app called 'MoleculAR' (version 1.1.3) was downloaded by the I group onto their mobile device for use with the digital AR prompt. The app selected provided the full functionality required to support the AR learning task, containing the necessary attributes of allowing participants to drag and pinch with their fingers when manipulating the perspectives of the geometric shapes that are aligned to the human movement effect. The body movement from the handheld device further enabled participants to reorient the position of the phone's camera relative to the 3D model generated, adding to the human movement effect experienced (refer to Figure 4).

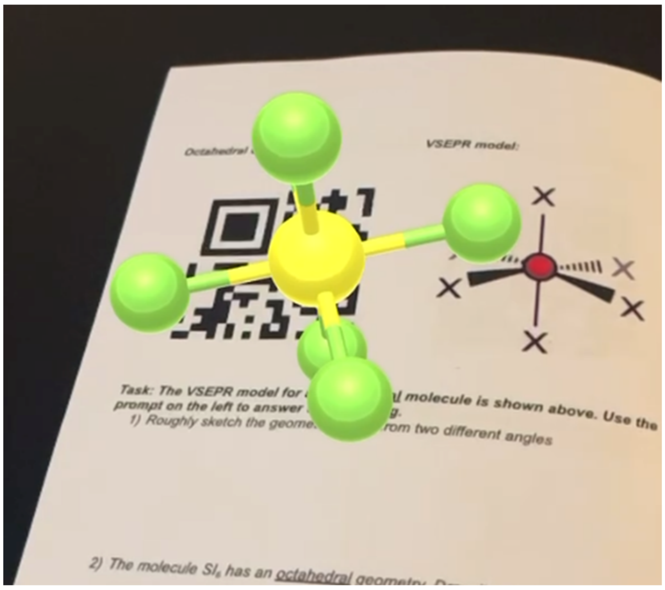

Figure 4. Example of AR app being used with learning booklet.

2.3. Validity and Reliability

The validity of the content delivery and testing phases of data collection were assured by aligning the content of the study with the relevant learning outcomes from the state curriculum implemented at the school. Careful selection of the year group was considered, as participants needed a certain level of prerequisite understanding without having been introduced to the content itself. A Year 10 cohort was ultimately selected, as the content from the curriculum is introduced in Year 11. The appropriateness of this choice was further informed by prior pilot testing undertaken with a younger cohort. Interpretation of the statistical analysis of this data suggested an inadequate level of pre-existing knowledge present in the younger cohort for meaningful data to be obtained, ultimately guiding the final choice of participants. Reliability was considered by undertaking data collection within the familiar environment of the participants' school during schooling hours, in addition to the prior pilot testing, to circumvent potential issues such as fatigue, nervousness, and misinterpretation of questions.

3. Results

Data from the study were analysed using IBM SPSS (Statistical Package for Social Science) Statistics. Cognitive load was scored numerically utilising a 9-point scale corresponding to the Likert scale options (from 0 = Too easy to 9 = Too difficult), and achievement in each phase of testing was scored as a value corresponding to their achievement on the test (as a score out of 14).

Achievement. Initial analyses indicated no significant main or interaction effects ($F < 1$ in most instances) associated with gender on either the achievement or cognitive load scores. The two groups did not diverge in pre-test scores ($F(1, 41) = 1.7$, ns). The achievement test data were analysed using *t*-test procedures. In both groups, the achievement scores increased from the pre-test to the two post-tests, respectively (dependent *t*s of 7.2 and 6.4, $p < 0.01$). The two groups differed significantly in the T4 post-test ($p = 0.02$), although differences in the baseline tests and initial T3 tests failed to achieve significance (see means and *t* values in Table 2).

Table 2. Statistical comparisons of intervention and control groups on achievement total and sub scores.

Time	Control ($n = 18$)	Intervention ($n = 24$)	t	p
T1 Pre-test achievement	2.72 (1.22)	3.42 (1.25)	1.8	0.08
T3 Post-test achievement	4.78 (1.35)	5.96 (2.22)	1.9	0.06
T4 Delayed post-test achievement	4.50 (2.09)	6.21 (2.49)	2.4	0.02

Cognitive load. A 2 × 3 repeated measures ANOVA, with time as the repeated measure, revealed a significant effect for time on cognitive load scores: $F(1, 40) = 83$, $p < 0.01$. Significant interaction between time and treatment, $F(1, 40) = 6.2$, $p = 0.02$, was found, indicating the impact of the treatment varied with time. It was evident that the two groups diverged in both the immediate and delayed post-tests, respectively: $F(1, 40) = 6.8$, $p = 0.01$ and $F(1, 40) = 7.12$, $p = 0.01$. The two groups did not differ at the pre-test level (see Table 3 for mean scores). An incidental finding is that the achievement scores correlated with the cognitive load scores on the two post-tests (-0.6, and -0.53); that is, as achievement increased, cognitive load decreased.

Table 3. Statistical comparisons of intervention and control groups on cognitive load total and sub scores.

Time	Control ($n = 18$)	Intervention ($n = 24$)	t	p
T1 Pre-test cognitive load	60.33 (5.80)	59.45 (6.86)	0.4	0.07
T3 Post-test cognitive load	52.66 (6.39)	43.95 (11.61)	3.1	0.004
T4 Delayed post-test cognitive load	51.44 (6.81)	42.38 (12.72)	3.0	0.005

4. Discussion

Similar to other studies using CLT and CTML principles to improve visuospatial processing by guiding task design, this study aimed to reduce any unnecessary visuospatial processing to highlight the benefits of using AR technology to positively impact schema acquisition and reduce participant-perceived cognitive load. While it was expected participants from both the I and C groups would interpret the mental rotation images and engage in similar cognitive activity, the results suggest participants who were provided with AR technology visualisations (I group) perceived less cognitive load and had moderately improved achievement scores, an inference of the AR technology being the only change in variable between the two groups. Those participants who did not engage in AR technology visualisations (C group) perceived higher cognitive load and did not achieve as highly in test achievement when compared to the I group.

Understanding this perceived reduction of cognitive load and moderately improved achievement by the I group within the framework of CLT principles would suggest those who experienced AR technology:

1. Had greater WM-available resources to undertake the learning activity by drawing upon schemas from the LTM;
2. Were able to process novel information gained during the task due to the availability of WM resources; and
3. Were able to transfer new schemas to the LTM.

The content used in the study was designed to target both I and C participants' prior knowledge to support the construction of new schemas within their existing cognitive architecture. Yet, the I group participants were able to apply mental rotation visualisations more freely, with less obstruction. The interpretation of the self-reporting data suggesting that those I group participants who experienced a lower level of cognitive load ultimately achieved improved learning results in part due to the greater availability of cognitive resources that could be assigned to the learning of new content material. This understanding is supported by other studies [52] involving the integration of new information to reduce cognitive load to maximise working memory resources, offering benefit to schema acquisition [53] and enhancing the integration of lower-level schemas together to form higher-level schemas with an increasing level of complexity and autonomy [54].

The participants' ability to use visuospatial representations and cueing may have also supported the drawing of the pre-requisite schemas required to interpret and experience these representations. Known as the signalling principle, this ability enables students to chunk pre-existing schemas, sometimes incorporating multiple representations into fewer elements or even a single element, freeing up cognitive resources. The lower level of cognitive load experienced encourages the I group to construct schemas, optimising the relationship observed between mental rotation and achievement in both phases of post-testing. This is congruent with other findings that demonstrate the effectiveness that AR technology can have in reducing the level of cognitive load influence by mental rotation when applied to studying three-dimensional structures at the molecular level [11]. It also reiterates claims regarding the efficacy of the technology to increase learning gains in molecular chemistry [55].

A significant feature of the AR technology required students to use a mobile device utilising AR technology and required hand movements to touch the screen to rotate the three-dimensional molecular structures. Finger movement and manipulation, a commonly evolved automated skill, requires very few WM resources and enables students to move the 3D molecular geometry content with little instruction due to the intuitive design features based on CLT principles. The use of innate and evolved physical resources, such as the use of fingers to manipulate objects, can be applied to manipulating geometric shapes on a mobile device and is aligned with the human movement effect. The lower performance from the C group participants who did not engage in AR technology would suggest that they were not able to engage in mental rotation visualisation as successfully when compared to the I group. The instructional approach used by the C group implies that many of the C participants' WM resources were depleted during the instructional phase of the task and while attempting to mentally rotate the molecular geometry rather than being applied to solving the problem and creating and transferring new schemas to their LTM.

Limitations and Future Research

Due to logistical restraints, the sample size of the study was limited. Extending the scope of the study to incorporate more participants in future studies could allow for additional meaningful insights and strengthen the confidence in the conclusions drawn. Mental rotation abilities have been observed to vary due to a number of factors, including socio-economic status, education level, and language [14]. Future directions could consider the relationship between AR-based learning interventions designed using CLT principles and these additional factors by collecting data from a more diverse range of contexts. The method of collecting cognitive load measurements using a Likert scale also comes with inherent limitations [56]. Future directions could incorporate alternate or additional measurements of cognitive load, e.g., through measurements of individual types of cognitive load or via direct physiological measurements. A mixed-method approach to CLT research could also yield interesting insight [57,58], where the incorporation of items such as open-ended questions in the data collection may allow for more complex inferences to take shape.

5. Conclusions

This study investigated the effect of AR technology using mobile devices containing instructional 3D molecular geometry content, designed based on CLT principles, to encourage hand movements to rotate three-dimensional molecular structures. Statistical analysis using SPSS revealed that AR technology improved the ability of participants to mentally rotate molecular geometries and perceive less cognitive load. The study found mental rotation ability has an effect on cognitive load, but cognitive load can be altered using AR technology.

The optimised implementation of AR technology within the context of the study requires careful consideration. CTML suggests that active engagement is required to construct internal mental representations when processing multiple representations of external information [59]. Processing and drawing referential connections between multiple representations, such as those composed with AR learning, imposes high cognitive expenses [60]. Further investigation is required to determine whether this technology becomes more beneficial to participants who are less adept in their visuospatial abilities or to those who have mental rotation mastery. The possibility of creating specific content tailored to both lower and higher levels of expertise may prove to add more benefit to the application of AR in the classroom. Additionally, further investigation is required to establish whether other subject areas that require mental rotation, such as mathematical spatial reasoning, may also benefit from the use of AR technology.

The study provides a strong rationale for the application of AR technology when teaching chemistry and three-dimensional spatial arrangements of matter at the molecular level. The benefits of using AR technology can be explained from both the human movement effect and the signalling principle, highlighting its advantageous and beneficial effects on student learning.

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Data Availability Statement: Requests to access the data should be directed to the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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