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Enhancing high school students' understanding of molecular geometry with augmented reality

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Abstract

Augmented reality (AR) has emerged as a promising technology for supporting chemistry education by providing interactive and engaging visualizations of abstract concepts. This study investigated the effectiveness of an AR-based learning module developed using the Blippar platform for teaching molecular geometry to high school students. A quasi-experimental design was employed, with 49 students assigned to either the AR intervention or traditional instruction. Pre- and post-tests, surveys, and interviews were conducted to assess students' conceptual understanding, spatial reasoning, perceptions, and experiences. The results showed that the AR group significantly outperformed the control group in terms of measures of content knowledge and spatial ability. Students reported high levels of satisfaction, engagement, and intention to use AR for learning chemistry. The design features and instructional strategies that facilitated effective learning with AR were identified, including scaffolding, multiple representations, and real-world applications. However, technical challenges and the need for integration with other pedagogical approaches were also noted. The findings contribute to the theoretical and empirical foundations of AR in chemistry education and provide practical implications for the design and implementation of AR-based learning experiences in this domain. Future research should investigate the long-term impacts, individual differences, and collaborative aspects of learning with AR in chemistry.

Keywords

augmented reality, chemistry education, molecular geometry, spatial reasoning, conceptual understanding, Blippar, multimedia learning, instructional design, mixed-methods research, secondary education

1. Introduction

Visualization plays a crucial role in chemistry education, as it aids students in understanding abstract concepts and complex spatial relationships [27, 50]. However, many students struggle with mentally visualizing and manipulating three-dimensional

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structures, which can hinder their comprehension of fundamental chemical principles [11, 47]. Traditional instructional methods, such as textbook illustrations and physical models, have limitations in conveying dynamic and interactive representations of chemical phenomena [31, 46].

Augmented reality (AR) has emerged as a promising technology to address these challenges by overlaying virtual content onto the real world, creating immersive and interactive learning experiences [4, 25]. In science and chemistry education, AR has been applied to visualize molecular structures, chemical reactions, and laboratory equipment, among other topics [10, 38, 53]. Research suggests that AR can enhance students' spatial abilities, conceptual understanding, and motivation in chemistry learning [1, 13, 26].

Despite the growing interest in AR for chemistry education, there is a need for more empirical studies that investigate the design, implementation, and effectiveness of AR-based learning interventions in diverse contexts [19, 52]. Furthermore, the affordances and limitations of specific AR platforms and tools, such as Blippar, still need to be explored in the literature [29, 36].

The present study aims to address these gaps by developing and evaluating an AR-based learning module for teaching molecular geometry using the Blippar app. Specifically, we seek to answer the following research questions:

RQ1: How does the use of an AR-based module affect students' understanding of molecular geometry concepts compared to traditional instruction?
RQ2: What are students' perceptions and experiences of learning with the AR-based module?
RQ3: What design features and instructional strategies support effective learning with the AR-based module?

2. Theoretical background

2.1. Cognitive load theory and multiple representations

Cognitive load theory (CLT) posits that human working memory has limited capacity and that instructional designs should manage cognitive load to facilitate learning [37, 44]. In chemistry education, students often struggle with the cognitive demands of processing multiple representations, such as chemical symbols, formulas, and structures [28, 45]. AR can help reduce extraneous cognitive load by integrating representations in a coherent and interactive format, allowing students to focus on essential information [9, 51].

The use of multiple representations is central to chemistry learning, as students need to develop fluency in translating between macroscopic, submicroscopic, and symbolic levels of representation [27, 30]. However, novice learners often have difficulty coordinating multiple representations and making connections across levels [3, 31]. AR can support representational competence by providing dynamic and linked representations that make explicit the relationships between concepts [40].

2.2. Situative learning and embodied cognition

Situative learning theories emphasize the role of context, social interaction, and authentic activities in knowledge construction [8, 32]. AR can create situated learning experiences by embedding virtual content in real-world settings, enabling students to explore chemical phenomena in contextualized and collaborative ways [12, 17]. For example, AR can simulate laboratory experiments, allowing students to manipulate variables and observe reactions without safety risks [16, 26].

Embodied cognition theories suggest that learning is grounded in sensorimotor experiences and that bodily interactions can enhance conceptual understanding [23, 49]. AR affords embodied learning opportunities by engaging students in physical actions, such as gestures and spatial navigation, to interact with virtual objects [33]. In chemistry, AR can enable embodied experiences of molecular structures and dynamics, supporting spatial reasoning and problem-solving [1].

2.3. AR applications in chemistry education

Several studies have investigated the use of AR in chemistry education, demonstrating its potential to enhance visualization, engagement, and conceptual understanding. For example, Cai, Wang and Chiang [10] developed an AR-based learning tool for teaching the structure and composition of substances, finding that it improved students' performance and attitudes compared to traditional instruction. Similarly, Chen and Liu [13] used an AR application to support students' learning of chemical reactions, reporting increased motivation and knowledge gains.

Blippar is an AR platform that has been used in educational contexts, including chemistry. Karnishyna et al. [29] used Blippar to create AR content for teaching organic chemistry, finding that it increased students' motivation and facilitated the perception of abstract concepts.

However, there is a need for more empirical research on the design and implementation of AR in chemistry education, particularly using platforms like Blippar. Many existing studies focus on short-term interventions or specific topics, leaving open questions about the long-term effects and transferability of AR-based learning [19, 25]. Furthermore, the optimal design features and instructional strategies for AR in chemistry education still need to be explored, requiring further investigation [1, 26].

The current study aims to address these gaps by developing and evaluating a Blippar-based AR module for teaching molecular geometry, incorporating insights from cognitive load theory, multiple representations, situative learning, and embodied cognition.

3. Methodology

3.1. AR application development

We developed an AR-based learning module for teaching molecular geometry using the Blippar platform (see appendix A for development details). The module consists of a series of interactive 3D models and animations that illustrate the spatial arrangement of atoms in molecules, following the Valence Shell Electron Pair Repulsion (VSEPR) theory [22, 24]. The content was designed to align with the high school chemistry curriculum and learning objectives related to molecular geometry [6].

The AR module was created using Blippar's web-based tool, BlippBuilder, which allows for the integration of 3D models, animations, and interactive elements [5]. The 3D molecular models were generated using ChemDraw and exported in OBJ format [41]. The models were then imported into BlippBuilder and augmented with labels, descriptions, and animations to highlight key features and concepts (figure 1).

The design of the AR module was informed by principles of cognitive load theory, multiple representations, and embodied cognition [9, 33, 40]. To manage cognitive load, the module presents information incrementally and provides clear instructions and feedback [34]. Multiple representations, such as ball-and-stick models and

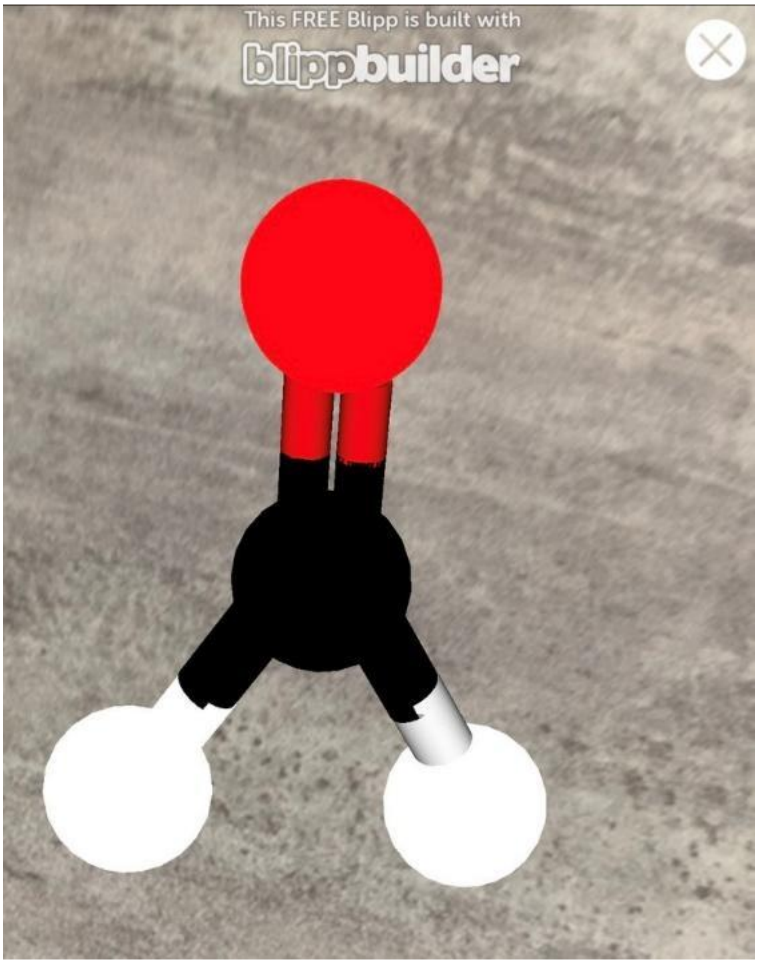

Figure 1: Screenshot of the AR module showing a 3D model of the molecule.

electrostatic potential maps, are used to support understanding of molecular structure and properties [30]. Embodied interactions, such as rotating and zooming in on molecules, are incorporated to encourage spatial reasoning and active learning [2].

3.2. Study context and participants

The study was conducted at a secondary school, No. 15, in Kryvyi Rih, Ukraine, during the 2021-2022 academic year. The school serves a diverse student population and offers chemistry as a required course for 10th-grade students. Two intact classes, taught by the same chemistry teacher, were selected to participate in the study. The classes were randomly assigned to either the treatment group (n=25), which used the AR module, or the control group (n=24), which received traditional instruction on molecular geometry.

The participants were 49 10th-grade students (26 females, 23 males) with an average age of 15.7 years (*SD*=0.6). Prior to the study, all students had completed introductory units on atomic structure and chemical bonding. Informed consent was obtained from the students and their parents/guardians, and the school administration approved the study.

3.3. Data collection and analysis

A mixed-methods approach was used to collect and analyze data on students' learning outcomes, perceptions, and experiences [14]. The following instruments were administered before and after the intervention:

- *Molecular geometry concept test* (MGCT, appendix B.1) – a 20-item multiple-choice test assessing students' understanding of VSEPR theory, molecular shapes, and polarity [21]. The test was validated by a panel of chemistry education experts from Kryvyi Rih State Pedagogical University and pilot-tested with a similar student population.
- *Student perceptions of AR survey* (SPARS, appendix B.2) – a 15-item Likert-scale survey measuring students' perceived usefulness, ease of use, enjoyment, and intention to use AR for learning chemistry [42]. The survey was adapted from existing instruments and showed good reliability (Cronbach's α is 0.87).
- Semi-structured interviews (appendix B.3). A purposive sample of 12 students (6 from each group) was interviewed using Zoom to gain deeper insights into their learning experiences and perceptions. The interviews were recorded, auto-transcribed by Zoom with further manual checks by researchers, and coded using thematic analysis (appendix C.2) [7].

Quantitative data from the MGCT and SPARS were analyzed using descriptive statistics, independent-samples t-tests, and analysis of covariance (ANCOVA) to compare the treatment and control groups [20]. Qualitative data from the interviews were analyzed inductively to identify emerging themes and patterns, which were then triangulated with the quantitative findings [35].

4. Results

4.1. RQ1: Effects on students' understanding of molecular geometry

The first research question investigated the impact of the AR-based module on students' understanding of molecular geometry concepts compared to traditional instruction. Table 1 presents the descriptive statistics and independent samples t-test results for the MGCT scores.

Table 1
Descriptive statistics and t-test results for MGCT scores.

Group	Pre-test		Post-test		Gain	
	M	*SD*	*M*	*SD*	*M*	*SD*
Treatment (*n*=25)	8.24	2.91	16.52	2.43	8.28	2.59
Control (*n*=24)	8.08	3.12	13.67	3.01	5.58	2.73
t-test	$t(47)=0.18$, $p=0.86$		$t(47)=3.46$, $p<0.01$		$t(47)=3.38$, $p<0.01$	

The results show that while there was no significant difference between the groups on the pre-test, the treatment group scored significantly higher than the control group on the post-test and gained scores. An ANCOVA, controlling for pre-test scores, confirmed a significant effect of the AR intervention on post-test scores, $F(1,46)=14.27$, $p<0.001$, $\eta_p^2=0.24$ (appendix C.1).

Figure 2 illustrates the distribution of MGCT gain scores for each group using box plots. The treatment group exhibits a higher median and narrower interquartile range compared to the control group, indicating more consistent learning gains.

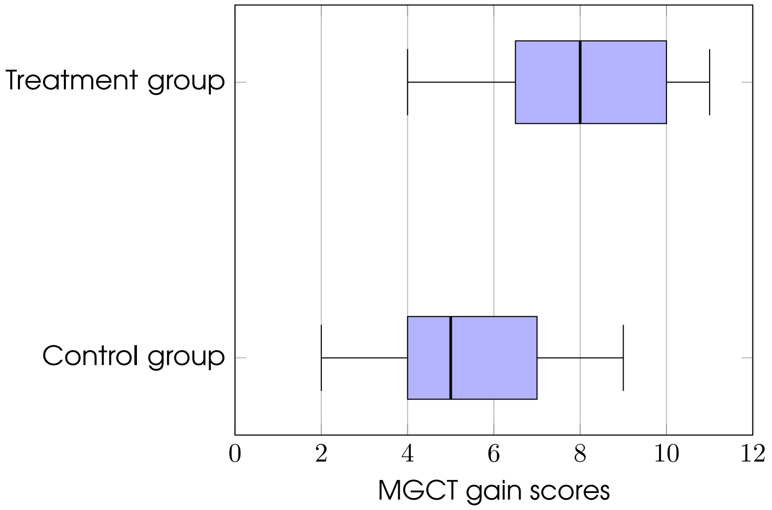

Figure 2: Box plots of MGCT gain scores for the treatment and control groups.

The qualitative findings from the interviews corroborate the quantitative results. Students in the treatment group reported a deeper understanding and retention of molecular geometry concepts, attributing this to the visualizations and interactions afforded by the AR module. For example:

> The AR app helped me see the 3D shapes of molecules more clearly. I could rotate them and see how the bond angles change with different numbers of electron pairs. It made the VSEPR rules easier to remember. (Student T14)

In contrast, some students in the control group expressed difficulty visualizing and applying the concepts learned through traditional methods:

> I understood the basic idea of VSEPR, but it was hard to picture the molecular shapes just from the textbook diagrams. I got confused when trying to predict the geometry for more complex molecules. (Student C09)

These findings suggest that the AR module enhanced students' spatial reasoning and conceptual understanding of molecular geometry, supporting the quantitative results.

4.2. RQ2: Students' perceptions and experiences

The second research question examined students' perceptions and experiences of learning with the AR-based module. Table 2 presents the descriptive statistics for the SPARS subscales (appendix B.2) and total scores.

The results indicate generally positive perceptions of the AR module, with high ratings on all subscales (above 4 on a 5-point scale). Students found the AR module useful for learning, easy to use, and enjoyable and expressed intention to use similar tools in the future.

The interview data provide further insights into students' experiences. Several themes emerged, including:

- *Engagement and motivation* – students appreciated the interactive and "game-like" nature of the AR module, which made learning more engaging and motivating compared to traditional methods.

Table 2
Descriptive statistics for SPARS subscales and total scores.

Subscale	No. of Items	*M*	*SD*
Perceived usefulness	4	4.12	0.63
Perceived ease of use	3	4.28	0.59
Enjoyment	4	4.36	0.61
Intention to use	4	4.02	0.71
Total	15	4.19	0.57

> Using the AR app made learning chemistry more fun and interesting. It didn't feel like studying but more like exploring and discovering. (Student T03)

- *Autonomy and self-paced learning* – the AR module allowed students to manipulate molecules at their own pace, fostering a sense of autonomy and supporting individual learning needs.

  > I liked being able to control the pace and go back to review concepts if needed. With the AR app, I could spend more time on the parts I found challenging. (Student T21)

- *Collaborative learning* – although designed for individual use, the AR module prompted students to discuss and compare their understandings with peers, facilitating collaborative learning.

  > My friend and I would often show each other the molecules we created in the AR app and talk about the shapes and angles. It helped us learn from each other. (Student T08)

However, some students also reported initial technical difficulties or disorientation when using the AR module:

> It took me a while to get used to the AR interface and controls. Sometimes, the tracking wasn't smooth, or the models would glitch. (Student T16)

These findings highlight AR's potential to enhance student engagement and autonomy while also identifying areas for improvement in the user experience and technical implementation.

4.3. RQ3: Design features and instructional strategies

The third research question explored the design features and instructional strategies that supported effective learning with the AR-based module. Analysis of the interviews revealed several key findings:

- *Scaffolding and feedback* – the module provided scaffolding in the form of hints, prompts, and feedback, which guided students' interactions and reinforced key concepts. Students who used these features more frequently tended to perform better on the MGCT.

  > The hints in the AR app helped me when I got stuck. They didn't give away the answer but pointed me in the right direction. (Student T11)

- *Multiple representations* – the use of multiple representations, such as ball-and-stick models and electron density maps, supported students' understanding by presenting information in different ways. Students often switched between representations to clarify their thinking.

  > I found the electron density maps useful for seeing the shape of the molecule. The ball-and-stick model showed the bond angles more clearly. Using both helped me understand better. (Student T23)

- *Contextual examples* – the module included real-world examples and applications of molecular geometry, such as in drug design and materials science. Students found these examples motivating and relevant to their interests.

  > I liked learning about how molecular shape affects the properties of medicines and new materials. It made the concepts feel more meaningful and applicable. (Student T07)

These findings suggest that effective AR design for chemistry learning should incorporate scaffolding, multiple representations, and contextually relevant examples. The usage patterns and student feedback can inform future iterations and implementations of the AR module.

5. Discussion

The findings of this study demonstrate the potential of AR, explicitly using the Blippar platform, to enhance students' understanding and engagement in learning molecular geometry. The positive effects on conceptual knowledge and spatial reasoning align with previous research on AR in chemistry education [10, 13, 25]. The AR module provided students with interactive 3D visualizations and multiple representations, which supported their ability to manipulate mentally and reason about molecular structures. This is consistent with the principles of spatial cognition and representational competence in chemistry learning [18, 30, 50].

The design of the AR module, informed by cognitive load theory and multimedia learning principles [34, 44], likely contributed to its effectiveness. The use of scaffolding, feedback, and segmentation helped manage intrinsic cognitive load, while the integration of 3D models and information reduced extraneous load. The contextually relevant examples and real-world applications may have promoted germane load by increasing students' motivation and engagement [37]. These findings suggest that careful instructional design, grounded in learning theories, is crucial for realizing the benefits of AR in chemistry education.

Students' positive perceptions and experiences with the AR module, as evidenced by the survey and interview data, underscore the motivational and affective advantages of this technology. The high ratings for enjoyment, ease of use, and intention to use AR align with previous studies on student attitudes toward AR in science learning [1, 16, 26]. The qualitative themes of engagement, autonomy, and collaboration that emerged from the interviews resonate with the affordances of AR identified in the literature, such as increased motivation, self-directed learning, and social interaction [12, 17, 39]. These findings highlight the potential of AR to create more student-centered and interactive learning environments in chemistry education.

However, the study also revealed some limitations and challenges of using Blippar for AR in chemistry learning. Some students reported technical difficulties or initial disorientation with the AR interface, which may have hindered their learning experience. This echoes concerns raised in previous studies about the usability and technical robustness of AR applications in education [16, 25, 51]. While Blippar offers an accessible and user-friendly platform for creating AR content, it may not have all the features or stability required for seamless educational implementation. Educators and researchers should carefully consider the technical requirements and limitations of AR tools when designing and deploying them in chemistry classrooms.

The findings also suggest that AR should not be seen as a standalone solution but rather as a complementary tool that is integrated with other instructional strategies and resources. The AR module in this study was used in conjunction with traditional lectures, textbook readings, and group discussions, which likely contributed to its effectiveness. This is consistent with the idea of AR as a “bridge” between physical and virtual learning environments, rather than a replacement for either [12, 51]. Future research should explore how AR can be optimally blended with other pedagogical approaches and technologies to support chemistry learning.

In terms of implications for theory, this study’s findings support the application of spatial cognition, multimedia learning, and representational competence theories to the design and evaluation of AR interventions in chemistry. The study also highlights the need for further theoretical development to explain the unique affordances and constraints of AR as a learning technology, such as its ability to merge physical and virtual contexts and to support embodied interactions [33, 39].

For research, this study demonstrates the value of mixed-methods designs and multiple data sources in investigating the effects and mechanisms of AR in chemistry education. The combination of quantitative measures (e.g., concept tests and surveys) and qualitative insights (e.g., interviews and observations) provided a more comprehensive and nuanced understanding of students’ learning outcomes, perceptions, and experiences. Future research should build on this approach to examine the long-term impacts, transfer effects, and individual differences in learning with AR [25, 39].

In terms of practical implications, this study offers several recommendations for educators and instructional designers interested in using AR, particularly with Blippar, for chemistry education:

- Ground the design of AR content and activities in learning theories and research-based principles, such as cognitive load theory, multimedia learning, and spatial cognition.
- Use AR to provide interactive 3D visualizations, multiple representations, and contextually relevant examples that support students’ conceptual understanding and spatial reasoning.
- Integrate scaffolding, feedback, and segmentation strategies to manage cognitive load and guide students’ interactions with the AR content.
- Blend AR with other instructional strategies and resources, such as lectures, discussions, and hands-on activities, to create a coherent and balanced learning experience.
- Provide technical support and training for students and teachers to ensure smooth and effective use of AR tools in the classroom.
- Continuously evaluate and improve the AR interventions based on student feedback, learning outcomes, and usage patterns to optimize their educational value.

6. Conclusion

This study investigated the effectiveness of an AR-based learning module developed using Blippar for teaching molecular geometry to high school chemistry students.

The findings demonstrate that the AR intervention significantly improved students' conceptual understanding and spatial reasoning compared to traditional instruction. Students reported positive perceptions and experiences with the AR module, highlighting its benefits for engagement, autonomy, and collaborative learning. The design features and instructional strategies that supported effective learning with AR were identified, including scaffolding, multiple representations, and contextually relevant examples.

The study contributes to the theoretical and empirical foundations of AR in chemistry education by providing evidence for this technology's cognitive and affective advantages and insights into the design principles and pedagogical approaches that optimize its effectiveness. The findings support the application of cognitive load theory, multimedia learning, and spatial cognition theories to the development and evaluation of AR interventions in this domain.

However, the study also revealed some limitations and challenges, such as technical difficulties and the need for integration with other instructional strategies. The sample size and duration of the intervention were limited, and the long-term impacts and transfer effects of learning with AR were not assessed. Future research should address these limitations by conducting large-scale, longitudinal studies that examine the retention and application of knowledge gained through AR in chemistry education.

Other directions for future work include investigating individual differences in learning with AR, such as prior knowledge, spatial ability, and learning styles, to personalize and adapt the AR experiences. The potential of AR for supporting collaborative and inquiry-based learning in chemistry also warrants further exploration, as well as the integration of AR with other emerging technologies, such as virtual reality and artificial intelligence.

References

[1] Abdinejad, M., Talaie, B., Qorbani, H.S. and Dalili, S., 2021. Student Perceptions Using Augmented Reality and 3D Visualization Technologies in Chemistry Education. *Journal of Science Education and Technology*, 30(1), pp.87–96. Available from: https://doi.org/10.1007/s10956-020-09880-2.

[2] Abrahamson, D., 2014. Building educational activities for understanding: An elaboration on the embodied-design framework and its epistemic grounds. *International Journal of Child-Computer Interaction*, 2(1), pp.1–16. Available from: https://doi.org/10.1016/j.ijcci.2014.07.002.

[3] Ainsworth, S., 2006. DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction*, 16(3), pp.183–198. Available from: https://doi.org/10.1016/j.learninstruc.2006.03.001.

[4] Azuma, R.T., 1997. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, 6(4), pp.355–385. Available from: https://doi.org/10.1162/pres.1997.6.4.355.

[5] Blippar Group Limited, 2024. Create & Build AR | Blippbuilder Free 3D Augmented Reality Tool - Blippar. Available from: https://www.blippar.com/build-ar.

[6] Bobkova, O.S., Bukhtiiarov, V.K., Valiuk, V.F., Velychko, L.P., Dubovyk, O.A., Pavlenko, V.O. and Puhach, S.V., 2017. Chemistry. 10-11 grades. Profile level: Curriculum for institutions of general secondary education. Available from: https://mon.gov.ua/storage/app/media/zagalna%20serednya/programy-10-11-klas/2018-2019/ximiya-10-11-profilnij-riven.docx.

[7] Braun, V. and Clarke, V., 2006. Using thematic analysis in psychology. *Qualitative*

Research in Psychology, 3(2), pp.77–101. Available from: https://doi.org/10.1191/1478088706qp063oa.

[8] Brown, J.S., Collins, A. and Duguid, P., 1989. Situated Cognition and the Culture of Learning. *Educational Researcher*, 18(1), pp.32–42. Available from: https://doi.org/10.3102/0013189X018001032.

[9] Bujak, K.R., Radu, I., Catrambone, R., MacIntyre, B., Zheng, R. and Golubski, G., 2013. A psychological perspective on augmented reality in the mathematics classroom. *Computers & Education*, 68, pp.536–544. Available from: https://doi.org/10.1016/j.compedu.2013.02.017.

[10] Cai, S., Wang, X. and Chiang, F.K., 2014. A case study of Augmented Reality simulation system application in a chemistry course. *Computers in Human Behavior*, 37, pp.31–40. Available from: https://doi.org/10.1016/j.chb.2014.04.018.

[11] Cavin, C.S., Cavin, E.D. and Lagowski, J.J., 1981. The effect of computer-assisted instruction on the attitudes of college students toward computers and chemistry. *Journal of Research in Science Teaching*, 18(4), pp.329–333. Available from: https://doi.org/10.1002/tea.3660180407.

[12] Chen, P., Liu, X., Cheng, W. and Huang, R., 2017. A review of using Augmented Reality in Education from 2011 to 2016. In: E. Popescu, Kinshuk, M.K. Khribi, R. Huang, M. Jemni, N.S. Chen and D.G. Sampson, eds. *Innovations in Smart Learning*. Singapore: Springer Singapore, Lecture Notes in Educational Technology, pp.13–18. Available from: https://doi.org/10.1007/978-981-10-2419-1_2.

[13] Chen, S.Y. and Liu, S.Y., 2020. Using augmented reality to experiment with elements in a chemistry course. *Computers in Human Behavior*, 111, p.106418. Available from: https://doi.org/10.1016/j.chb.2020.106418.

[14] Creswell, J.W. and Plano Clark, V.L., 2017. *Designing and Conducting Mixed Methods Research*. 3rd ed. SAGE Publications.

[15] Davis, F.D., 1989. Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly*, 13(3), pp.319–340. Available from: https://doi.org/10.2307/249008.

[16] Domínguez Alfaro, J.L., Gantois, S., Blattgerste, J., De Croon, R., Verbert, K., Pfeiffer, T. and Van Puyvelde, P., 2022. Mobile Augmented Reality Laboratory for Learning Acid–Base Titration. *Journal of Chemical Education*, 99(2), pp.531–537. Available from: https://doi.org/10.1021/acs.jchemed.1c00894.

[17] Dunleavy, M., Dede, C. and Mitchell, R., 2009. Affordances and Limitations of Immersive Participatory Augmented Reality Simulations for Teaching and Learning. *Journal of Science Education and Technology*, 18(1), pp.7–22. Available from: https://doi.org/10.1007/s10956-008-9119-1.

[18] Ebner, M. and Holzinger, A., 2007. Successful implementation of user-centered game based learning in higher education: An example from civil engineering. *Computers & Education*, 49(3), pp.873–890. Available from: https://doi.org/10.1016/j.compedu.2005.11.026.

[19] Faridi, E., Ghaderian, A., Honarasa, F. and Shafie, A., 2021. Next generation of chemistry and biochemistry conference posters: Animation, augmented reality, visitor statistics, and visitors' attention. *Biochemistry and Molecular Biology Education*, 49(4), pp.619–624. Available from: https://doi.org/10.1002/bmb.21520.

[20] Field, A., 2017. *Discovering Statistics Using IBM SPSS Statistics*. 5th ed. SAGE Publications. Available from: http://repo.darmajaya.ac.id/5678/.

[21] García Franco, A. and Taber, K.S., 2009. Secondary Students' Thinking about Familiar Phenomena: Learners' explanations from a curriculum context where 'particles' is a key idea for organising teaching and learning. *International Journal*

of Science Education, 31(14), pp.1917–1952. Available from: https://doi.org/10.1080/09500690802307730.

[22] Gillespie, R.J., 1992. The VSEPR model revisited. *Chemical Society Reviews*, 21, pp.59–69. Available from: https://doi.org/10.1039/CS9922100059.

[23] Glenberg, A.M., 2010. Embodiment as a unifying perspective for psychology. *WIREs Cognitive Science*, 1(4), pp.586–596. Available from: https://doi.org/10.1002/wcs.55.

[24] Housecroft, C.E. and Sharpe, A.G., 2005. *Inorganic Chemistry*. 2nd ed. Pearson.

[25] Ibáñez, M.B. and Delgado-Kloos, C., 2018. Augmented reality for STEM learning: A systematic review. *Computers & Education*, 123, pp.109–123. Available from: https://doi.org/10.1016/j.compedu.2018.05.002.

[26] Irwansyah, F.S., Yusuf, Y.M., Farida, I. and Ramdhani, M.A., 2018. Augmented Reality (AR) Technology on The Android Operating System in Chemistry Learning. *IOP Conference Series: Materials Science and Engineering*, 288(1), p.012068. Available from: https://doi.org/10.1088/1757-899X/288/1/012068.

[27] Johnstone, A.H., 1991. Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, 7(2), pp.75–83. Available from: https://doi.org/10.1111/j.1365-2729.1991.tb00230.x.

[28] Johnstone, A.H., 2000. Teaching of chemistry – logical or psychological? *Chemistry Education Research and Practice*, 1(1), pp.9–15. Available from: https://doi.org/10.1039/A9RP90001B.

[29] Karnishyna, D.A., Selivanova, T.V., Nechypurenko, P.P., Starova, T.V. and Stoliarenko, V.G., 2022. The use of augmented reality in chemistry lessons in the study of “Oxygen-containing organic compounds” using the mobile application Blippar. *Journal of Physics: Conference Series*, 2288(1), p.012018. Available from: https://doi.org/10.1088/1742-6596/2288/1/012018.

[30] Kozma, R., 2003. The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction*, 13(2), pp.205–226. External and Internal Representations in Multimedia Learning. Available from: https://doi.org/10.1016/S0959-4752(02)00021-X.

[31] Kozma, R.B., 2000. The Use of Multiple Representations and the Social Construction of Understanding in Chemistry. In: M.J. Jacobson and R.B. Kozma, eds. *Innovations in Science and Mathematics Education: Advanced Designs for Technologies of Learning*. Mahwah, NJ: Erlbaum, pp.11–46. Available from: https://www.academia.edu/42103279.

[32] Lave, J. and Wenger, E., 1991. *Situated Learning: Legitimate Peripheral Participation*, Learning in Doing: Social, Cognitive and Computational Perspectives. Cambridge: Cambridge University Press. Available from: https://doi.org/10.1017/CBO9780511815355.

[33] Lindgren, R. and Johnson-Glenberg, M., 2013. Emboldened by Embodiment: Six Precepts for Research on Embodied Learning and Mixed Reality. *Educational Researcher*, 42(8), pp.445–452. Available from: https://doi.org/10.3102/0013189X13511661.

[34] Mayer, R.E., 2020. *Multimedia Learning*. 3rd ed. Cambridge: Cambridge University Press. Available from: https://doi.org/10.1017/9781316941355.

[35] Miles, M.B., Huberman, A.M. and Saldaña, J., 2014. *Qualitative Data Analysis: A Methods Sourcebook*. 3rd ed. SAGE Publications. Available from: https://www.metodos.work/wp-content/uploads/2024/01/Qualitative-Data-Analysis.pdf.

[36] Nechypurenko, P.P., Semerikov, S.O. and Pokhliestova, O.Y., 2023. An augmented reality-based virtual chemistry laboratory to support educational and research activities of 11th grade students. *Educational Dimension*, 8, p.240–264. Available from: https://doi.org/10.31812/educdim.4446.

[37] Paas, F., Gog, T. van and Sweller, J., 2010. Cognitive Load Theory: New Conceptualizations, Specifications, and Integrated Research Perspectives. *Educational Psychology Review*, 22(2), pp.115–121. Available from: https://doi.org/10.1007/s10648-010-9133-8.

[38] Pence, H.E., 2010. Smartphones, Smart Objects, and Augmented Reality. *The Reference Librarian*, 52(1-2), pp.136–145. Available from: https://doi.org/10.1080/02763877.2011.528281.

[39] Radu, I., 2014. Augmented reality in education: a meta-review and cross-media analysis. *Personal and Ubiquitous Computing*, 18(6), pp.1533–1543. Available from: https://doi.org/10.1007/s00779-013-0747-y.

[40] Rau, M.A., 2015. Enhancing undergraduate chemistry learning by helping students make connections among multiple graphical representations. *Chemistry Education Research and Practice*, 16, pp.654–669. Available from: https://doi.org/10.1039/C5RP00065C.

[41] Revvity Signals Software, 2024. ChemDraw. Available from: https://revvitysignals.com/products/research/chemdraw.

[42] Schutera, S., Schnierle, M., Wu, M., Pertzel, T., Seybold, J., Bauer, P., Teutscher, D., Raedle, M., Heß-Mohr, N., Röck, S. and Krause, M.J., 2021. On the Potential of Augmented Reality for Mathematics Teaching with the Application cleARmaths. *Education sciences*, 11(8), p.368. Available from: https://doi.org/10.3390/educsci11080368.

[43] Semerikov, S.O., Vakaliuk, T.A., Mintii, I.S., Hamaniuk, V.A., Soloviev, V.N., Bondarenko, O.V., Nechypurenko, P.P., Shokaliuk, S.V., Moiseienko, N.V. and Shepiliev, D.S., 2022. Immersive E-Learning Resources: Design Methods. *Digital Humanities Workshop*. New York, NY, USA: Association for Computing Machinery, DHW 2021, p.37–47. Available from: https://doi.org/10.1145/3526242.3526264.

[44] Sweller, J., 1994. Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction*, 4(4), pp.295–312. Available from: https://doi.org/10.1016/0959-4752(94)90003-5.

[45] Taber, K.S., 2008. Towards a Curricular Model of the Nature of Science. *Science & Education*, 17(2), pp.179–218. Available from: https://doi.org/10.1007/s11191-006-9056-4.

[46] Tasker, R., 2014. Research into practice: Visualising the molecular world for a deep understanding of chemistry. *Teaching science*, 60(2), pp.16–27.

[47] Vesna Ferk, Margareta Vrtacnik, A.B. and Gril, A., 2003. Students' understanding of molecular structure representations. *International Journal of Science Education*, 25(10), pp.1227–1245. Available from: https://doi.org/10.1080/0950069022000038231.

[48] Vlasenko, K.V., Lovianova, I.V., Volkov, S.V., Sitak, I.V., Chumak, O.O., Krasnoshchok, A.V., Bohdanova, N.G. and Semerikov, S.O., 2022. UI/UX design of educational on-line courses. *CTE Workshop Proceedings*, 9, p.184–199. Available from: https://doi.org/10.55056/cte.114.

[49] Wilson, M., 2002. Six views of embodied cognition. *Psychonomic Bulletin & Review*, 9(4), pp.625–636. Available from: https://doi.org/10.3758/BF03196322.

[50] Wu, H.K., Krajcik, J.S. and Soloway, E., 2001. Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching*, 38(7), pp.821–842. Available from: https://doi.org/10.1002/tea.1033.

[51] Wu, H.K., Lee, S.W.Y., Chang, H.Y. and Liang, J.C., 2013. Current status, opportunities and challenges of augmented reality in education. *Computers & Education*, 62, pp.41–49. Available from: https://doi.org/10.1016/j.compedu.

2012.10.024.
[52] Zhai, X. and Jackson, D.F., 2023. A pedagogical framework for mobile learning in science education. In: R.J. Tierney, F. Rizvi and K. Ercikan, eds. *International Encyclopedia of Education*. 4th ed. Oxford: Elsevier, pp.215–223. Available from: https://doi.org/10.1016/B978-0-12-818630-5.13037-4.
[53] Zhang, J., Li, G., Huang, Q., Feng, Q. and Luo, H., 2022. Augmented Reality in K–12 Education: A Systematic Review and Meta-Analysis of the Literature from 2000 to 2020. *Sustainability*, 14(15), p.9725. Available from: https://doi.org/10.3390/su14159725.

A. AR module development details

The AR module was developed using the Blippar platform, which allows for the creation and deployment of interactive AR content. The development process involved the following steps:

1. **Content design**. The learning objectives and key concepts related to molecular geometry were identified based on the high school chemistry curriculum [6]. Storyboards and scripts were created to outline the structure and flow of the AR content.
2. **3D modeling**. The molecular structures were created using ChemDraw and exported as FBX/OBJ files. The 3D models were then imported into Blender for editing and optimization, including the addition of colours, textures, and animations.
3. **UI/UX design**. The user interface and interaction design were created using Sketch and Adobe XD. The layout, icons, and navigation elements were designed to be intuitive and user-friendly, following AR design principles and guidelines [43, 48].
4. **AR development**. The 3D models, UI elements, and interactivity were integrated using the Blippar Studio tool. The AR markers were generated and linked to the corresponding content. The AR experiences were tested and refined through iterative prototyping and user feedback.
5. **Deployment and testing**. The AR module was published to the Blippar app (codes 1989195, 1989195, 1989281, 1989295, 1989240, 1989311, 2019779, 2019781, 1989261, 1989361, 2019792, 2019798, 1989373, 1989320, 2019794, 2019800, 1989378, 2019796, 2019805, 2019803) and tested on various devices to ensure compatibility and performance. User testing was conducted with a sample of high school students to gather feedback and make final improvements before the study.

B. Data collection instruments

B.1. Molecular geometry concept test (MGCT)

The MGCT is a 20-item multiple-choice test that assesses students' understanding of molecular geometry concepts, including VSEPR theory, molecular shapes, bond angles, and polarity. The test was developed by a team of chemistry education experts and validated through pilot testing and item analysis. The MGCT has a reliability coefficient (Cronbach's alpha) of 0.85.

Sample items:

- What is the molecular geometry of $BeCl_2$?
    1. Linear
    2. Bent
    3. Trigonal planar
    4. Tetrahedral
- Which of the following molecules has a dipole moment?
    1. CO_2
    2. CCl_4
    3. NH_3
    4. BCl_3

B.2. Student perceptions of AR survey (SPARS)

The SPARS is a 15-item Likert-scale survey that measures students' perceptions of the AR module in terms of its usefulness, ease of use, enjoyment, and intention to use. The survey was adapted from the technology acceptance model by Davis [15] and has a reliability coefficient (Cronbach's α) of 0.92.

Sample items (rated on a scale from 1 – strongly disagree to 5 – strongly agree):

- The AR app helped me understand molecular geometry better.
- The AR app was easy to use and navigate.
- I enjoyed learning with the AR app.
- I would like to use AR apps for learning chemistry in the future.

B.3. Interview protocol

Semi-structured interviews were conducted with a subset of students from each group to gather qualitative insights into their learning experiences and perceptions. The interviews lasted approximately 20-30 minutes and were audio-recorded and transcribed for analysis.

Sample questions:

- How did the AR app/traditional instruction help you understand molecular geometry?
- What did you like or dislike about learning with the AR app/traditional method?
- How did the AR app/traditional instruction influence your interest and engagement in learning chemistry?
- What challenges or difficulties did you encounter while using the AR app/learning with the traditional method?
- How do you think AR could be used to improve chemistry education in the future?

C. Additional data and analysis

C.1. ANCOVA Results

An analysis of covariance (ANCOVA) was conducted to compare the post-test scores of the AR and control groups, controlling for pre-test scores as a covariate. The assumptions of normality, homogeneity of variances, and homogeneity of regression slopes were met. The ANCOVA results are presented in table 3.

The ANCOVA results confirm that the AR group had significantly higher post-test scores than the control group, after controlling for pre-test scores, $F(1,46)=14.27$, $p<0.001$, partial $\eta^2=0.24$. This indicates that the AR intervention had a significant effect on students' learning outcomes beyond any initial differences in prior knowledge.

Table 3
ANCOVA results for the effect of AR on post-test scores.

Source	*SS*	*df*	*MS*	*F*	*p*
Pre-test	112.84	1	112.84	16.73	<0.001
Group	96.31	1	96.31	14.27	<0.001
Error	310.56	46	6.75		
Total	15271.00	49			

C.2. Thematic analysis of interview data

The interview transcripts were analyzed using thematic analysis, following the six-phase process outlined by Braun and Clarke [7]. The analysis involved familiarization with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. The main themes that emerged from the analysis are presented in table 4.

Table 4
Main themes and subthemes from the interview analysis.

Themes	Subthemes
Visualization and understanding	Spatial reasoning Multiple representations Molecular structure and properties
Engagement and motivation	Interactivity and exploration Real-world relevance Gamification and challenge
Usability and technical issues	Ease of use and navigation Technical glitches and bugs Device compatibility and performance
Integration with instruction	Blended learning Teacher guidance and support Collaborative and social learning

The thematic analysis provides a rich and nuanced understanding of student's experiences and perceptions of learning with AR, complementing the quantitative findings and informing the design and implementation of future AR interventions in chemistry education.