JOURNAL OF CHEMICAL EDUCATION

Open Access

pubs.acs.org/jchemeduc

Article

Using an Augmented Reality Learning Environment to Teach the Mechanism of an Electrophilic Aromatic Substitution

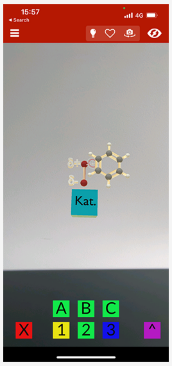
Martin Bullock,* Nicole Graulich, and Johannes Huwer

Cite This: *J. Chem. Educ.* 2024, 101, 1534−1543

Read Online

ACCESS | Metrics & More | Article Recommendations | ● Supporting Information

ABSTRACT: Last year, IUPAC named augmented reality (AR) as one of the top ten emerging technologies in chemistry for 2022 for chemistry research and teaching chemistry. Despite an increase in the number of studies investigating the use of AR to teach chemistry, there have only been a few studies on the use of AR to teach organic chemistry, especially the mechanism of chemical reactions. We designed an augmented reality learning environment (AR-LE) to teach the mechanism of an electrophilic aromatic substitution (EAS) by illustrating the macroscopic level of the reaction with a video of the experiment, a 2D-AR animation of the mechanism using Lewis structures (symbolic level), and a 3D-AR animation of the mechanism to illustrate the particulate level. The AR-LE was used in five different grade 12 chemistry classes in Germany in 2022. Students took a knowledge test before and after the lesson and answered survey questions regarding their cognitive load, their acceptance of the technology, and their attitude toward the use of the technology to learn chemistry. The findings reveal that students significantly increased their learning gains ($Z = 5.348$, $p < 0.001$). The calculated effect size of 0.8062 shows that the treatment had a large effect. Furthermore, their responses to the cognitive load and technology acceptance survey indicated that they did not experience high extraneous cognitive load and showed overall acceptance of the AR-LE.



KEYWORDS: *First-Year Undergraduate, Second-Year Undergraduate, Organic Chemistry, Multimedia-Based Learning, Mechanisms of Reactions*

■ INTRODUCTION

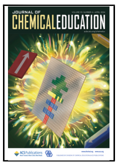
Learning chemistry is complex for students because they need to operate simultaneously on different levels of representations (macroscopic, submicroscopic, and symbolic) to understand phenomena thoroughly.[1] Experts in chemistry can move between these different representational levels with ease.[2] Students need help to relate what they see in the lab to events at the molecular level[3,4] and experience difficulties understanding concepts in organic chemistry and using those concepts to make predictions.[5] Thus, one of the primary goals of chemistry teaching is to help make invisible phenomena visible to students.

Augmented reality (AR) allows us to enrich the real world with additional digital information. It, thus, lies between the real world (reality) and the virtual world (virtual reality)[6] and is often referred to as "Mixed Reality". Czok et al.[7] extended Azuma's[8] definition of AR to include the requirements of real-time interactivity and functioning 3D rendering. While different technologies are used to realize AR,[9] the result is always digital information and reality viewed simultaneously on a screen. This screen could be a set of AR glasses such as Apple Vision Pro, for example, or the screen of a device such as a tablet or smartphone. In this case, the real environment is captured by the tablet camera and shown to the students on the screen, while the AR software shows the 3D AR objects on the device screen, making them appear as if they are being viewed in the room through the tablet camera. In this way, the AR content appears to be part of the real environment. The AR software can place the AR content in space by anchoring the content to a recognized printed image in the real environment, called "image-tracking", or by anchoring the content to a flat surface in the real environment by "world tracking".

A decade ago, studies indicated AR could enhance understanding of concepts about processes that could not be observed directly in nature.[10] In fact, in their 2014 review of AR trends in education, Bacca et al. found that (ref 11, p 139) *"AR has demonstrated to be effective when applied to...activities where students can see things that could not be seen in the real world or without a specialized device"*. The authors conclude that, based on their systematic review of the literature at the time, AR can be used to teach complex or abstract concepts effectively.

The use of AR is not a panacea, however. Like most learning technologies, careful consideration is required to ensure that the AR does not become a barrier to student learning. It is a powerful and flexible tool that can be deployed in many different forms; therefore, it is important to consider design

Received: September 7, 2023
Revised: February 3, 2024
Accepted: March 6, 2024
Published: March 18, 2024



https://doi.org/10.1021/acs.jchemed.3c00903
J. Chem. Educ. 2024, 101, 1534−1543

aspects to make appropriate learning and teaching scenarios. In their review, Krug et al.[12] found seven design parameters for AR teaching-learning scenarios: Immersion, Interactivity, and Congruence with Reality, Adaptivity, Game Elements, Complexity, and Content Proximity to Reality. Understanding the elements of design can guide the choice of augmented reality learning environments (AR-LEs) in the classroom and help determine the most appropriate ones for a student cohort, the nature of the concept to be learned, or the task. An adequately designed AR-LE, therefore, should acknowledge these design parameters as an asset for the learners and promote learning of the relevant concepts.

Despite an increasing number of studies suggesting the benefits of using AR to teach abstract concepts and despite its inclusion in the IUPAC top 10 emerging technologies in chemistry for 2022,[13] there have been only a few studies on the use of AR to teach organic chemistry,[14−16] and only one, to our knowledge, where AR is used to introduce a reaction mechanism in organic chemistry. In 2021, Keller et al.[17] investigated the differences in cognitive load—described in the next chapter—experienced by two intervention groups when learning three different topics in organic chemistry (stereochemistry, carbonyl chemistry, and pericyclic reactions) either with or without AR support. They found that the students learning with AR support experienced a lower intrinsic cognitive load (ICL) and extraneous cognitive load (ECL) than those who did not use AR support. Furthermore, they found no differences between the ICL and ECL experienced by either intervention group when comparing the results for learning stereochemistry to carbonyl chemistry. However, the results were different for the topic of the pericyclic reaction, which is more abstract and complex. While learning this mechanism, students with AR support experienced more ICL than in the first two lessons (on stereochemistry and carbonyl chemistry). In contrast, students without AR support showed no increase in the ICL for the third lesson on pericyclic reactions. Keller et al.[17] also note that the AR support group experienced far more germane cognitive load, the type of CL associated with deep learning, during the more complex topic than the students without AR support. The authors conclude that "the impact of AR-based learning increases with the complexity of the learning topic".[17]

In this paper, we present the results of a study conducted as part of a participatory action research project (PAR) conducted in 2022. The PAR model was introduced in 1989 by Whyte et al. for use in the social sciences[18] and was adapted for chemical education research as described by Eilks in 2002.[19] PAR proceeds in cycles of development, testing in practice, evaluation, reflection, and revision. The goal of PAR is to generate best practices in response to the actual needs of teachers; therefore, a comparison of the teaching with AR to teaching without AR is not warranted. Instead, it was important for us to develop an AR-LE that responded to the needs identified by the group of teachers and then evaluate it to ensure that it was helpful in teaching the identified topic to the relevant audience. Thus, this project is based on an intensive iterative collaboration with a select committee of expert chemistry teachers from several different schools throughout Baden-Württemberg and with the individual teachers who have volunteered to test the new learning environments in their classrooms. In 2021, we started to work collaboratively on developing AR-LE for a new addition to the upper-level chemistry curriculum: electrophilic aromatic substitution (EAS), specifically the catalyzed bromination of benzene. The goal was to teach students the mechanism of this substitution reaction and to contrast it with what they had already learned about the addition of bromine to alkenes. Throughout 2022, we worked with this committee of teachers to develop AR-LE for the high school chemistry curriculum in Baden-Württemberg. The teachers sketched a lesson plan for us to consult as we developed the AR-LE. We met regularly with the teachers to present the latest iteration of the AR-LE and responded to their feedback with improved versions at each meeting. This iterative process continued for four months before the first trial lesson.

To evaluate the effectiveness of this newly designed AR-LE, we measured student learning gain, the cognitive load experienced by the students, and their attitudes toward using AR. Thus, the study is guided by the following research questions and corresponding hypotheses:

RQ1: Does the use of this AR-LE help students learn the mechanism of the electrophilic aromatic substitution of bromine onto benzene?

H1: Students' scores on post-tests will be significantly better than scores on pretests taken before the intervention.

RQ2: What is the extent of the cognitive load experienced by students when working with this AR-LE?

H2: Students will experience minimal extraneous and elevated germane cognitive load.

RQ3: What is the extent of student technology acceptance when working with this AR-LE?

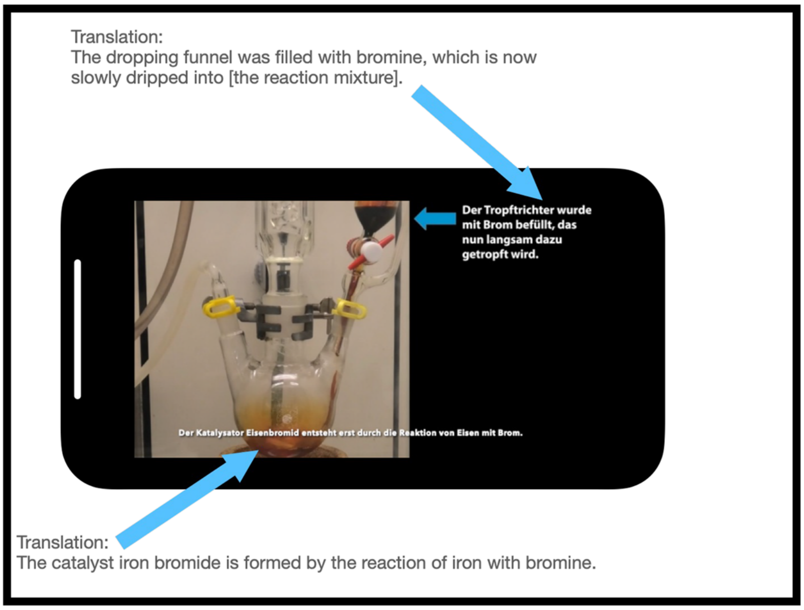
H3: Students will accept the use of AR in the teaching of the reaction mechanisms.

THEORETICAL CONSIDERATIONS

Levels of Representation

Johnstone's triangle is the well-known and widely used framework that proposes that phenomena in chemistry are represented on three levels (macroscopic, submicroscopic, and symbolic) in the classroom. Perhaps because of its popularity among chemistry instructors, there are many interpretations of Johnstone's triangle.[3,4] Johnstone himself wrote of three *levels*, which he called macroscopic, submicroscopic and symbolic,[1] and this is the interpretation we use in this study. The macroscopic level includes objects and events that students can see or touch. In contrast, the submicroscopic level is composed of invisible particles like molecules and ions, and the symbolic level includes, for example, formulas and equations we use to describe these phenomena.[3] While experienced chemists easily navigate between these three levels, students need to be explicitly taught how to connect them.

Taber[3] argues that the symbolic knowledge domain should not be considered "as a discrete 'level' of chemical knowledge that is one element of an ontological triad of macroscopic-submicroscopic-symbolic".[3] He points out that many components of the symbolic domain, for example, algebraic equations or graphs, constitute an additional demand on students as they try to learn chemistry. Furthermore, there are labels and symbols, for example, "hydrogen" or "H_2", which are ambiguous about whether the entities they are referring to are on the macroscopic (a sample of hydrogen gas) or submicroscopic (an individual molecule of hydrogen) level. Taber goes on to say that these ambiguous labels and symbols can be used as effective bridges between the macroscopic and submicroscopic, as long as teachers are explicit about what



Translation:
The dropping funnel was filled with bromine, which is now slowly dripped into [the reaction mixture].

Der Tropftrichter wurde mit Brom befüllt, das nun langsam dazu getropft wird.

Der Katalysator Eisenbromid entsteht erst durch die Reaktion von Eisen mit Brom.

Translation:
The catalyst iron bromide is formed by the reaction of iron with bromine.

Figure 1. Macroscopic representation of the electrophilic aromatic substitution (EAS) reaction.

level is being referred to.[3] In the next section of this paper, we will describe the AR-LE we designed to explicitly connect the macroscopic, submicroscopic, and symbolic representations of the mechanism of an EAS reaction.

Cognitive Load

When designing lessons and instructional materials, especially those that can be challenging either in terms of content knowledge or by use of highly dynamic displays, it is important to consider the Cognitive Load Theory (CLT). This theory is widely used and debated for evaluating learning environments and interpreting empirical results.[20] CLT is based on two assumptions about the two different types of memory that we use to learn—working memory, used to process information, and long-term memory, where information is stored.[21] While CLT assumes that long-term memory is "virtually unlimited",[20] working memory is assumed to be limited both in its capacity to process information and in the length of time that it can hold information. According to CLT, the demands on memory can be classified as one of three types of load: intrinsic cognitive load (ICL), extraneous cognitive load (ECL), and germane cognitive load (GCL).

ICL is the type of cognitive load that is related to the difficulty of the learning task. Generally, a teacher can only reduce the ICL of a lesson by removing material or changing the objectives. ECL, conversely, has to do with information that must be processed during a learning task that is not directly related to the learning objective. It is understood that lessons can be designed to minimize ECL. Poorly designed lessons that rely on technology unnecessarily are often high in ECL, for example. In their 2018 systematic review of AR for STEM learning, Ibáñez and Delgado-Kloos found that, while some studies showed that AR helped to decrease CL, the results were not always conclusive.[22] Furthermore, they found that AR sometimes had drawbacks, including promoting distraction and increasing ECL.[22] Ideally, every lesson would be designed to minimize ECL, but it is a critical consideration to include technology in the lesson. Since ICL cannot be easily reduced, the best way to ease the burden for students during the learning process is to design lessons and materials that minimize ECL and make it easier for them to engage in deep learning. The final type of cognitive load is GCL, which is the demand on learners as they perform the activities of deep learning and knowledge transfer. Given the different roles each of these types of cognitive load play in the learning process, it is helpful to be able to measure them separately.[20] In designing our AR-LE, our goal was to minimize ECL by explicitly connecting the macroscopic, submicroscopic, and symbolic representations of the mechanism of an EAS reaction.

Technology Acceptance Model and Student Attitudes

Another important theoretical underpinning of this study is the Technology Acceptance Model (TAM), which describes how users "come to accept and use a given technology".[23] Initially developed by Davis in 1989 to study why people accept or reject technology in the workplace,[24] it has been revised, extended, and modified to be used in various settings. The elements of the original TAM included perceived usefulness (PU), perceived ease of use (PEU), attitude toward using (AT), and behavioral intent to use (BI).[23] Typically, the TAM is used to evaluate new technologies in terms of their likelihood of being adopted by new users by examining PU, PEU, and AT and their influence on BI. The assumption is that "usability is a prerequisite to acceptance" of a technology.[23] Furthermore, PEU represents "the degree to which a technology will be free from effort",[21] cited by ref 23. Usability has been a problem identified in many studies of the use of AR to teach,[22,11] so much so that Bacca et al. called for more research into the "usability of AR applications in education as well as guidelines for designing AR-based educational settings".[11] Therefore, it is reasonable to measure students' responses to questions about these parameters, not to predict whether they will adopt the technology since that choice is made by the teacher rather than the students, but rather to discern how much effort students exert while using the technology. If students perceive our AR-LE as requiring little effort to use, that would be consistent with a lower ECL, which is one of our design goals.

It is reasonable to assume that the experience students have with technology during a lesson will affect their attitudes toward learning the material. Many researchers have sought to investigate the relationship between the two factors with mixed results. For example, Brown found a low correlation between the two,[25] and Elford found no correlation between attitude and academic achievement for students using AR to learn about VSEPR theory.[26] Meanwhile, others have found that attitude, among other noncognitive factors, can predict achievement in chemistry courses.[27−] If students report a positive attitude toward using our AR-LE to learn this reaction mechanism, it would be consistent with a lower ECL, which is one of our design goals.

AR DEVELOPMENT

For this study, we developed an AR-LE for the electrophilic substitution with video footage of the reaction in the lab, a 2D animation of the mechanism using familiar Lewis structures, and a 3D animation based on molecular models to represent the three representational levels of this reaction.[1]

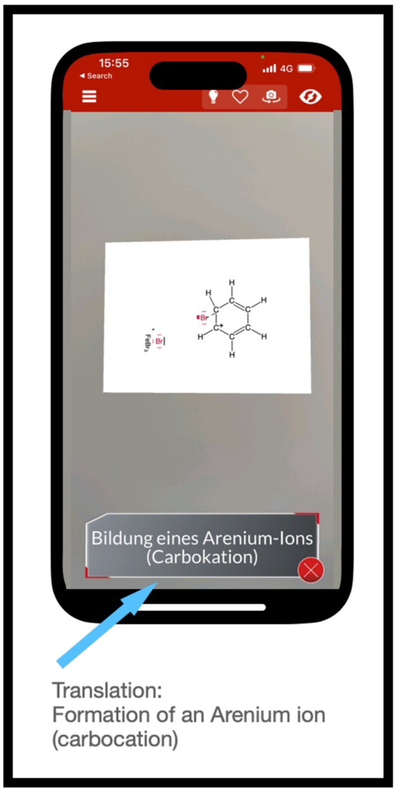
In addition to the design principles for AR outlined by Krug et al.,[12] we relied on the five design principles for developing visualization tools in chemistry as proposed by Wu and Shah in 2004 (ref 29, p 488): *"These principles include (1) providing multiple representations and descriptions, (2) making linked referential connections visible, (3) presenting the dynamic and interactive nature of chemistry, (4) promoting the transformation between 2D and 3D, and (5) reducing cognitive load by making information explicit and integrating information for students."*

Our video footage of the reaction shows the complete setup of the reaction with captions to label each component. Only key moments of the hours-long reaction are shown, e.g., the addition of bromine to benzene (see Figure 1), the addition of a catalyst, and observations indicating a reaction is taking place. Furthermore, three confirmation tests indicate the presence of HBr in the product mixture.

The symbolic level animations are dynamic versions of the Lewis structure diagrams often seen in textbooks that match the submicroscopic display of the reaction mechanism (see Figure 2).

Finally, the 3D animations illustrate the particulate level and the movements of the particles (Figure 3). In designing the animations, we focused on the interactivity design parameter highlighted by Schulmeister:[30] Learners should be able to view the reaction mechanisms, change how they are represented onscreen, and switch between the displayed reaction steps. Students can see all of these visualizations by scanning a proprietary barcode (Zapcode) with the free iOS or Android app Zappar. Zapcodes and materials for the lesson can be found at https://www.chemie.uni-konstanz.de/ag-huwer/forschung/downloads/augmented-reality/.[31]

Students could start, stop, rewind, and fast forward the video with familiar controls that appeared on the screen when touched. The 2D animations played in the plane of the paper and were designed to look like familiar static Lewis Structures that students know from their textbooks. The 3D animations were based on familiar molecular modeling kits that students had worked with in class previously. The 2D animations, designed to be viewed before the 3D animations, included text boxes on the screen, which briefly explained what was happening in each step of the mechanism. Viewing the 2D animations first, which are symbolic in nature, makes it easier for students to understand the 3D animations that represent the particulate level of the reaction mechanism. The 2D and 3D animations were presented in identical frames on the screen with the same control buttons for interactivity. Although the control buttons for both animations were shown with numbered buttons that indicate the reaction sequence, the students were free to view the animations in any sequence they wished and as many times as they wanted. To clarify the motion in the 3D animation, each step of the mechanism was divided into three substeps representing the particles immediately before, during, and immediately after the collision. By viewing both animations with identical control buttons, students could explicitly connect the steps of the reaction mechanism in the 2D animation, with its accompanying text boxes, with the 3D animation and its illustration of molecular motion.


Bildung eines Arenium-Ions (Carbokation)

Translation:
Formation of an Arenium ion (carbocation)

Figure 2. 2D animation of the EAS reaction mechanism.

We developed these visualizations in response to the needs of the teachers who developed the lesson plan for this new part of the curriculum. Each draft of the AR-LE was presented to the committee of teachers for their feedback in an iterative process until a final product was approved for classroom testing. The visualizations and accompanying lesson plan were tested in two different 12th grade classes in summer 2022. For the final trials in October, we made some changes to the AR-LE in response to feedback from students who did not like the limitation of having the animations tracked to images on the worksheets. While the animations themselves were unchanged, the entire AR-LE in the fall was "world-tracked" rather than "image-tracked" (spring version). As a result, students in the fall could anchor the animation to any horizontal surface rather than to a recognized image on paper to anchor the image.

EXPERIMENTAL DESIGN

Once this final version of the AR-LE was agreed upon, it was deployed in classrooms and evaluated in a pretest−post-test experimental design. To answer RQ1, we used a concept-

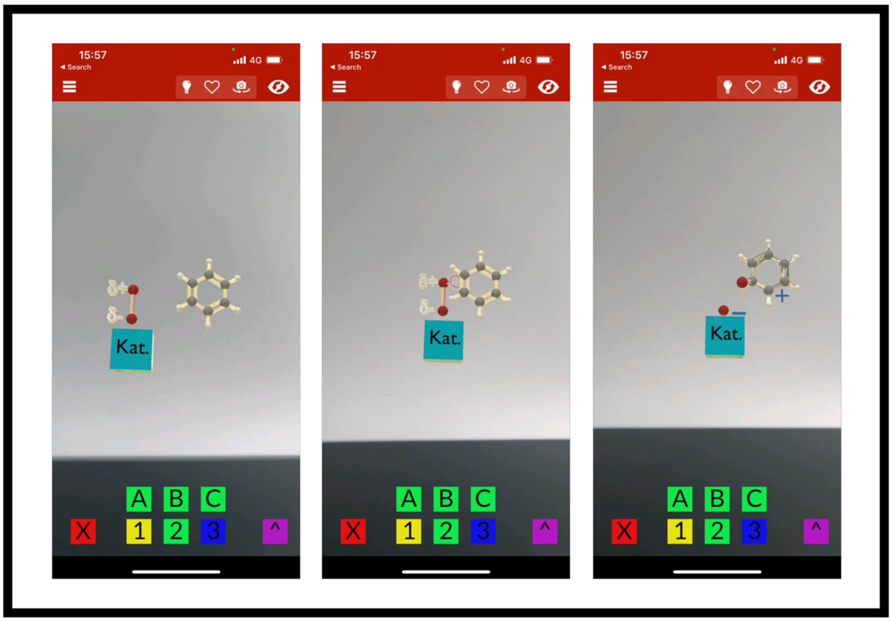


Figure 3. After viewing the 3D animation of steps 2 or 3 of the mechanism, students can view still shots of the attack particles immediately before, during, and after the collision by clicking the letter buttons above the number buttons. Screen shots for (2A) left, (2B) middle, and (2C), right. The catalyst is represented as a cube labeled "Kat.".

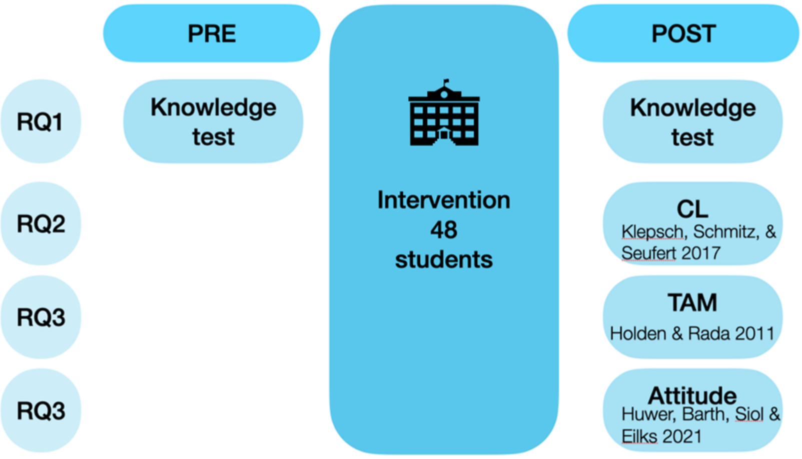


Figure 4. Experimental design

knowledge test to measure students' learning gain with the AR-LE. To answer RQ2, we used an established instrument from Klepsch et al. to measure the cognitive load (CL) experienced by the students during the intervention. Finally, to answer RQ3, we used an established instrument to measure students' perceptions of the ease of use of the AR-LE and their attitude toward using it to learn the mechanism of the relevant reaction. The goal of this participatory action research project was to develop an effective AR-LE, not to compare it to other methods of teaching the same material; therefore, no control group was warranted.

Learning Gain

We used a pretest and post-test designed with the teachers to measure learning gain. The version of the test used in the spring of 2022 included two questions that required students to understand conjugated pi-systems to answer them correctly. Those questions were removed from the version of the knowledge test in the fall of 2022 and replaced with questions about the reaction between bromine and a simple alkene. The tests were graded with rubrics, and only the questions used in both versions were further analyzed for learning gain. For example, students were asked to write reaction equations for the mechanism of electrophilic substitution of bromine on benzene using Lewis Structures. Students were also asked to describe the reaction mechanism of electrophilic substitution on benzene using the following technical terms: polarization, arenium ionization, and rearomatization. An English translation of the questions from this assessment can be found in the Supporting Information.

Cognitive Load

To measure CL, we used a questionnaire designed by Klepsch et al. CL theory is widely used in educational research to evaluate learning environments. Since CL theory was introduced by Sweller and Chandler in 1991,[21] many different methods for measuring CL have been deployed. Still, until 2017, none of those methods enabled the differential

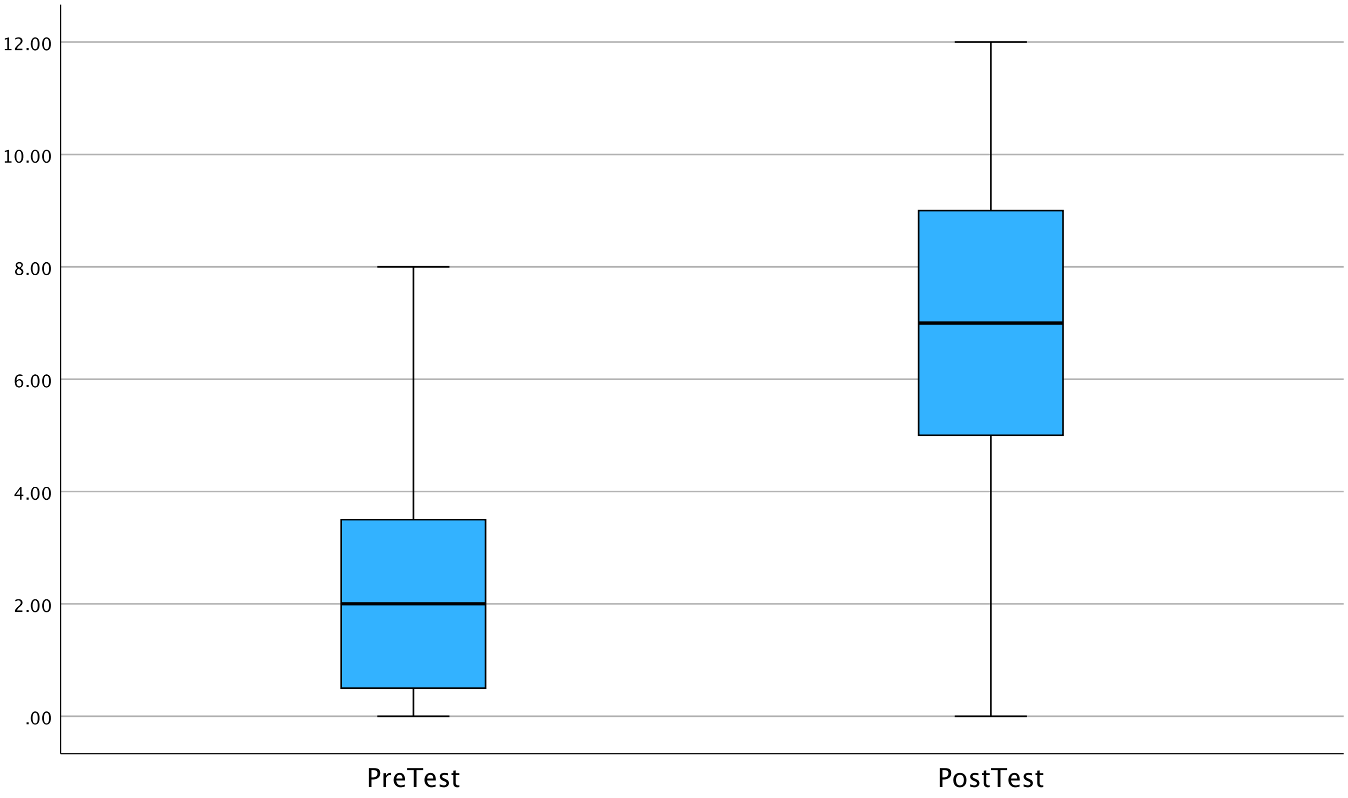


Figure 5. Box plot for pre- and post-test scores on the knowledge test.

measurement of the three types of CL with an instrument that was reliable and not limited to one domain or subject area. Klepsch et al. developed two different questionnaires to measure the CL experienced by students: the "informed rating" (by students who knew about the three different types of CL) and the "naïve rating" (by students who did not know about the three different types of CL). Both versions were analyzed for reliability, validity, and internal consistency. We used the "naïve rating" since the students in our study did not know about the three types of CL. There are a total of eight questions: two for ICL, three for GCL, and three for ECL. All questions were based on a 7-point Likert scale. This instrument was originally developed in German; therefore, translating the text of the questions was not necessary for our data collection.

Technology Acceptance and Attitude

To investigate the students' technology acceptance of AR, we used a German translation of the TAM survey developed by Holden and Rada[23] for use in educational settings (see Supporting Information). The instrument is divided into three sections for PU, PEU, and AT but does not measure BI, as the original TAM did. Instead, it includes four additional usability metrics in the PEU section of the survey. This is important to our study because the PEU measures the extent to which users deem the use of a technology to be "free from effort". These items within each section were highly consistent, with Cronbach's alpha values ranging from 0.874 to 0.940. To further investigate students' attitudes toward the use of AR, we used 7-point Likert questions developed by Huwer et al.[32] All questions from these instruments were combined into one paper-pencil survey, which was distributed to students immediately after the lesson.

■ DATA COLLECTION

The experimental design and instruments are illustrated in Figure 4. Students were given the pre- and post-test within 1 week of the lesson. Eighteen students took both the pre- and post-tests in the spring, and 26 students took both tests in the fall. All students were in their final year of high school and their second year of chemistry study. All students in the fall were advanced chemistry students, whereas ten students in the spring were advanced chemistry students, and eight were standard-level chemistry students who met for fewer hours each week. The pre- and post-knowledge tests were graded with a binary rubric by the first author, and the scores were analyzed with SPSS.

Students answered the paper-pencil surveys to collect cognitive load, technology acceptance, and attitude, as described above, after the lesson within 1 week of the intervention. The responses of each student were coded as numbers from 1 to 7 and entered into Excel for analysis.

■ DATA ANALYSIS

H1: Students' Scores on Post-tests Will Be Significantly Better than Scores on Pretests Taken before the Intervention

To test H1, pre- and post-test scores of all students were analyzed with SPSS using the Wilcoxon signed rank test for related samples. A total of 44 students submitted both a pretest and a post-test. This sample size is large enough to detect a statistical difference between the pretest scores and the post-test scores.

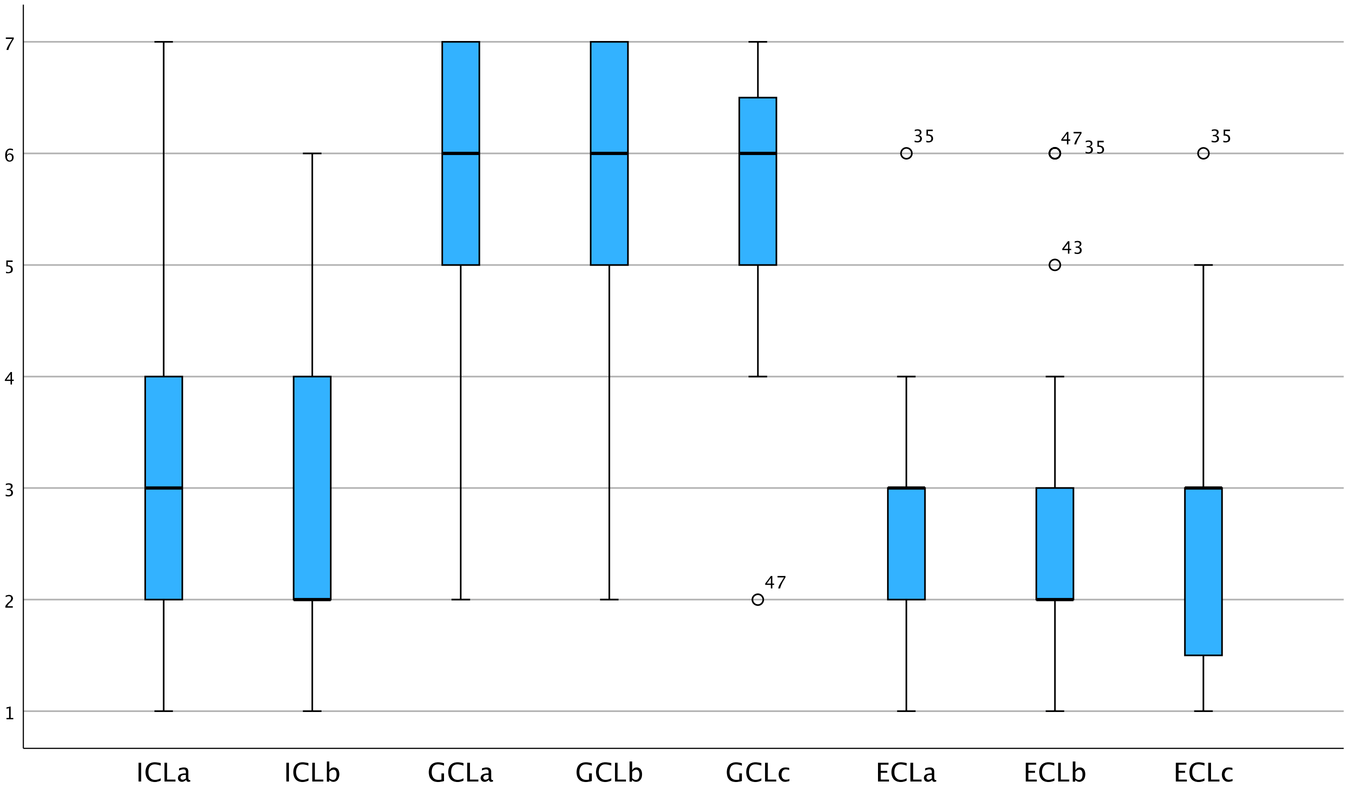


Figure 6. Box plot for composite scores for CL questions, showing the extent to which students experienced the different types of CL. A score of 7 is the highest rating, a score of 1 is the lowest rating, and a score of 4 is a neutral rating.

H2: Students Will Experience Minimal Extraneous and Elevated Germane Cognitive Load

H3: Students Will Accept the Use of AR in the Teaching of Reaction Mechanisms

To test H2 and H3, we analyzed students' responses to the paper-pencil survey, which included questions from the instruments used to measure cognitive load, technology acceptance, and student attitudes. Questions dealing with CL were analyzed individually to discern the extent to which the students experienced each type of CL in keeping with the design of the instrument that we used. A composite score was calculated for each instrument dealing with technology acceptance and attitude. To calculate the composite score, all the values of a student's responses in each instrument were summed and then divided by the number of responses given for that instrument, as described by Likert.[33] If a student did not respond to any questions in that instrument, then no score was calculated for the analysis. For questions that were phrased such that a lower integer answer indicated a positive response to the AR, the responses were transformed to the corresponding value on the scale where larger values indicate a stronger positive response; e.g., a score of 2 on such a question was transformed to a 6, for the purpose of calculating a composite sore. In this way, composite scores for each instrument could be calculated for each student such that a higher composite score represented a more positive response to the AR. Box plots for the composite scores for each questionnaire were created in SPSS.

■ RESULTS AND DISCUSSION

Our first hypothesis, H1, is supported by the pre- and post-test scores, while the results from the student surveys support our second and third hypotheses, H2 and H3. Overall, students showed a statistically significant learning gain, did not experience a high extraneous cognitive load, and showed acceptance of the AR-LE.

H1: Students' Scores on Post-tests Will Be Significantly Better than Scores on Pretests Taken before the Intervention

Pre- and post-test scores of all students were analyzed with SPSS using Wilcoxon signed rank test for related samples. The students' scores on the post-test were significantly better than those on the pretest ($N = 44$, $Z = 5.348$, $p < 0.001$). The calculated effect size of 0.8062 shows that the treatment had a large effect.

Box plots for the test results can be seen in Figure 5. The median post-test score is greater than the maximum pretest score.

Students showed a statistically significant learning gain, and we can take this as an indicator that the AR-LE helped students learn the related content. It is important to note that the goal of PAR is to generate the best practices. These results indicate that this is an effective way to teach this topic to the intended audience.

H2: Students Will Experience Minimal Extraneous and Elevated Germane Cognitive Load

Regarding our second question about the cognitive load experienced by the students, their responses to the questions indicate that they did not experience a high extraneous cognitive load. Students' ratings of their experienced cognitive load are presented by the respective type: ICL, ECL, and GCL, in Figure 6. The median scores for ICL and ECL are all 3 or 2. The median scores for questions about GCL are all 6. The range of scores for the questions rating ICL is broad, but the

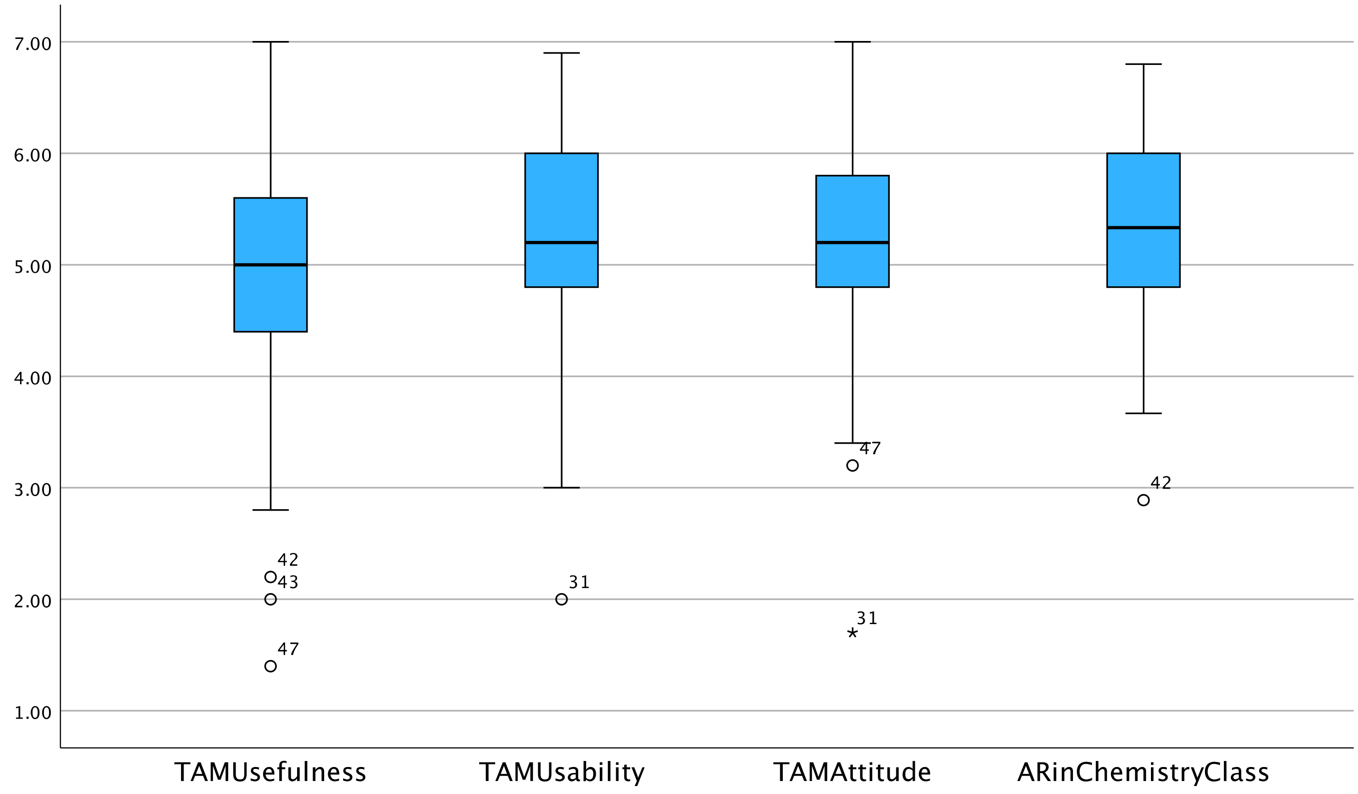


Figure 7. Box plot for composite scores of all students for questions about student attitudes and acceptance of technology. A score of 7 is the most positive rating, a score of 1 is the most negative rating, and a score of 4 is a neutral rating.

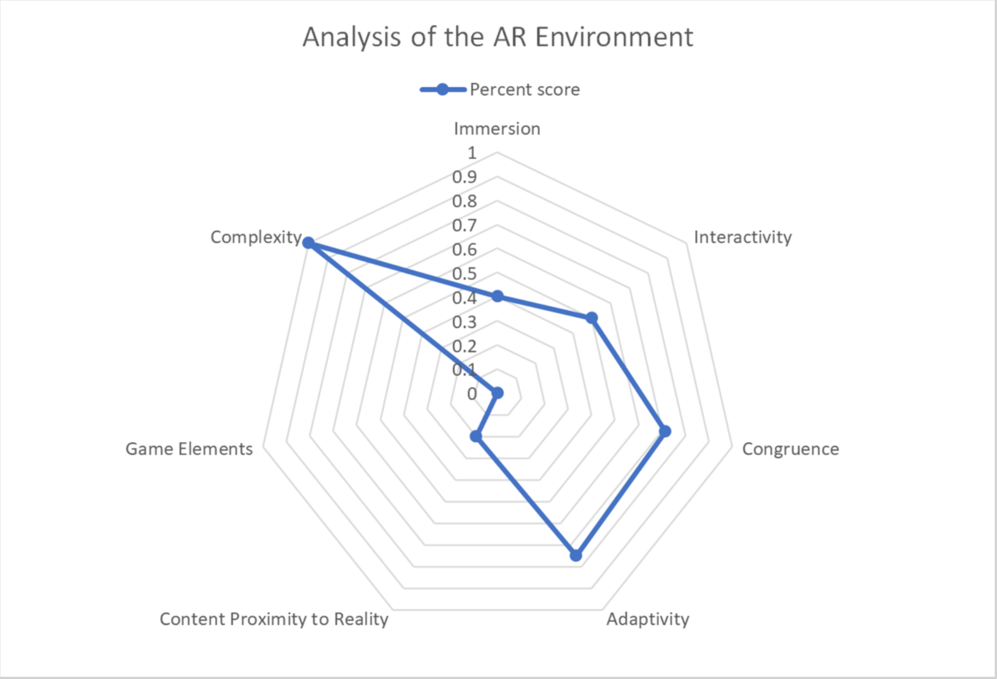


Figure 8. Diagram showing the proportional score from Krug et al.[12] analysis of the AR learning environment.

median scores are 3 for the first question and 2 for the second question, corresponding with low ICL. The range of scores for the questions rating GCL is similarly broad, and the median scores are all 6, which corresponds to a high GCL. The scores for the first two questions about ECL are more tightly distributed than the scores for the other types of CL, and the median scores for all three ECL questions are 3 or below. We therefore conclude that, overall, the students experienced low ECL and high GCL during their work with the AR-LE. These results are consistent with the findings of Keller et al.[17] regarding the role of AR in student learning of more abstract and complex topics in organic chemistry.

H3: Students Will Accept the Use of AR in the Teaching of Reaction Mechanisms

As for the students' attitudes about the AR-LE, their responses were positive overall. Figure 7 shows that the median responses for all TAM questions, as well as the questions about students' attitudes toward using AR in chemistry class, are 5 or higher, with the majority of scores ranging from 4 to 7. This means that, overall, the students viewed the AR-LE as useful and usable and had a positive attitude toward their learning experience with it. Previous research results on student attitudes toward the use of AR have been mixed.[25−28] These results support the notion that students are generally positive about using AR to learn chemistry.

Figure 7 illustrates the box plots for the composite scores for the questions regarding student attitude and technology acceptance. Outliers (responses that are 1.5 times greater or less than the interquartile range) are represented by circles, while extreme outliers (responses that are 3 times greater or less than the interquartile range) are represented by asterisks.

LIMITATIONS

Since we could not compare the AR-LE with a non-AR-LE, the implications that can be drawn concerning the variable AR are limited. The purpose of this study was not to develop an AR-LE that was more effective than some other types of learning environments. Instead, the purpose was to respond to the needs of teachers who intended to use AR to teach a reaction mechanism and to develop an AR-LE that could be used to teach it effectively. Furthermore, our results can be generalized only for AR-LEs that are similarly constructed to the AR-LE we presented. Not all AR-LEs are comparable. To enable a comparison with similar AR-LEs, we applied the evaluation grid by Krug et al.[12] to visually summarize the characteristics of our AR-LE (see Figure 8). If another AR-LE is comparable to ours in these parameters, similar results should be expected, according to Krug et al.[12] For example, the results we report in this article could not be generalized to an AR-LE with a high degree of immersion and game elements but low complexity, since our AR-LE is complex and has a low degree of immersion and no game elements at all. This visualization is not used to evaluate the quality or effectiveness of AR-LEs; rather, it is only used to classify AR-LEs so that teachers can choose them or researchers can compare them according to their characteristics.

CONCLUSIONS

The AR-LE presented here was evaluated by testing three hypotheses. After reviewing the results, we can conclude that this AR-LE can be used to teach grade 12 chemistry students the mechanism of the electrophilic aromatic substitution of bromine onto benzene. Student scores on the post-test were significantly higher than their pretest scores. Students experienced low ECL and high GCL values during the lessons. Furthermore, students accept the AR-LE and its use as a tool for teaching chemistry. We can conclude that the AR-LE does not impose a high ECL on students.

Presenting the AR-LE along the three representational levels according to Johnstone (macroscopic, submicroscopic, and symbolic levels) can as well be used separately in teaching. Depending on the respective learning objective, each of the three sections of the AR-LE can be used individually with their own teaching materials, separately or together with the deployment of the individual ZapCodes. This study's findings are consistent with insights into using AR-supported learning in other studies and illustrate that the designed AR-LE facilitated the learning process. It thus contributed to the growing body of research that supports the use of AR to teach complex concepts such as organic chemistry reaction mechanisms.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00903.

German translation of original TAM questions (PDF; DOCX)

English translation of the downloads page of our research group's Web site (PDF; DOCX)

English translation of the questions used for pre- and post-tests (PDF; DOCX)

AUTHOR INFORMATION

Corresponding Author

Martin Bullock − *University of Konstanz, Chair of Science Education, 78464 Konstanz, Germany; Thurgau University of Education, Department of Chemistry, 8280 Kreuzlingen, Switzerland;* orcid.org/0000-0001-9842-5514; Email: martin.bullock@uni-konstanz.de

Authors

Nicole Graulich − *Justus-Liebig-University Giessen, Institute of Chemistry Education, 35392 Giessen, Germany;* orcid.org/0000-0002-0444-8609

Johannes Huwer − *University of Konstanz, Chair of Science Education, 78464 Konstanz, Germany; Thurgau University of Education, Department of Chemistry, 8280 Kreuzlingen, Switzerland;* orcid.org/0000-0002-4271-7822

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.3c00903

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors would like to thank all the teachers and students who volunteered to participate in this study, especially the five teachers who participated in the iterative design of this AR-LE: Daniela Schliebitz, Markus Seitz, Matthias Seitz, Kai-Arwed Unger, and Karsten Wiese.

REFERENCES

(1) Johnstone, A. H. Why is science difficult to learn? Things are seldom what they seem. *J. Comput. Assist. Learn.* **1991**, *7*, 75−83.

(2) Kozma, R.; Russell, J. Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena. *J. Res. Sci. Teach.* **1997**, *34* (9), 949−968.

(3) Taber, K. S. Revisiting the chemistry triplet: drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chem. Educ. Res. Pract.* **2013**, *14* (2), 156−168.

(4) Talanquer, V. Macro, Submicro, and Symbolic: The many faces of the chemistry "triplet". *Int. J. Sci. Educ.* **2011**, *33* (2), 179−195.

(5) Graulich, N. The tip of the iceberg in organic chemistry classes: how do students deal with the invisible? *Chem. Educ. Res. Pract.* **2015**, *16*, 9−21.

(6) Milgram, P.; Takemura, H.; Utsumi, A.; Kishino, F. Augmented reality: a class of displays on the reality-virtuality continuum. *Proc. SPIE 2351, Telemanipulator and Telepresence Technologies*; 1995; DOI: 10.1117/12.197321.

(7) Czok, V.; Krug, M.; Müller, S.; Huwer, J.; Kruse, S.; Müller, W.; Weitzel, H. A Framework for Analysis and Development of Augmented Reality Applications in Science and Engineering Teaching. *Education Sciences.* **2023**, *13* (9), 926.

(8) Azuma, R. T. A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments.* **1997**, *6* (4), 355−385.

(9) Tschiersch, A.; Krug, M.; Huwer, J.; Banerji, A. ARbeiten mit erweiterter Realität im Chemieunterricht − ein Überblick über Augmented Reality in naturwissenschaftlichen Lehr-Lernszenarien. *CHEMKON.* **2021**, *28* (6), 241−244.

(10) Cheng, K. H.; Tsai, C. C. Affordances of augmented reality in science learning: Suggestions for future research. *J. Sci. Educ. Technol.* **2013**, *22* (4), 449−462.

(11) Bacca, J.; Baldiris, S.; Fabregat, R.; Graf, S.; Kinshuk. Augmented Reality trends in education: A systematic review of research and applications. *J. Educ. Technol. Soc.* **2014**, *17* (4), 133−149.

(12) Krug, M.; Czok, V.; Huwer, J.; Weitzel, H.; Müller, W. Challenges for the design of augmented reality applications for science teacher education. *INTED2021 Proceedings* **2021**, No. 6, 2484−2491.

(13) Gomollón-Bel, F. IUPAC Top Ten Emerging Technologies in Chemistry 2022. Discover the innovations that will transform energy, health, and materials science, to tackle the most urgent societal challenges and catalyse sustainable development. *Chemistry International.* **2022**, *44* (4), 4−13.

(14) Garzón, J.; Pavón, J.; Baldiris, S. Systematic review and meta-analysis of augmented reality in educational settings. *Virtual Reality.* **2019**, *23*, 447−459.

(15) Chang, H.; Binali, T.; Liang, J.; Chiou, G.; Cheng, K.; Lee, S.; Tsai, C. Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Comput. Educ.* **2022**, *191*, 104641.

(16) Mazzuco, A.; Krassmann, A. L.; Reategui, E.; Gomes, R. S. A systematic review of augmented reality in chemistry education. *Review of Education.* **2022**, *10*, 3325−3351.

(17) Keller, S.; Rumann, S.; Habig, S. Cognitive Load Implications for Augmented Reality Supported Chemistry Learning". *Information.* **2021**, *12* (3), 96−115.

(18) Whyte, W.; Greenwood, D.; Lazes, P. Participatory Action Research Through Practice to Science in Social Research. *American Behavioral Scientist* **1989**, *32*, 513−551.

(19) Eilks, I. Participatory Action Research in chemical education - A research design and experiences with its application. In *Proceedings of the 2nd International Conference on Science Education*; Cyprus Ministry of Education and Culture: Nicosia, 2002; pp 156−167.

(20) Klepsch, M.; Schmitz, F.; Seufert, T. Development and Validation of Two Instruments Measuring Intrinsic, Extraneous, and Germane Cognitive Load. *Front. Psychol.* **2017**, *8*, 1997−2014.

(21) Sweller, J.; Chandler, P. Evidence for Cognitive Load Theory. *Cogn. Instr.* **1991**, *8*, 351−362.

(22) Ibáñez, M.; Delgado-Kloos, C. Augmented reality for STEM learning: A systematic review. *Comput. Educ.* **2018**, *123*, 109−123.

(23) Holden, H.; Rada, R. Understanding the Influence of Perceived Usability and Technology Self-Efficacy on Teachers' Technology Acceptance. *J. Res. Technol. Educ.* **2011**, *43*, 343−367.

(24) Davis, F. D. Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS Quarterly.* **1989**, *13* (3), 319−340.

(25) Brown, S.; White, S.; Sharma, B.; Wakeling, L.; Naiker, M.; Chandra, S.; Gopalan, R.; Bilimoria, V. Attitude to the study of chemistry and its relationship with achievement in an introductory undergraduate course. *Journal Of The Scholarship Of Teaching And Learning.* **2015**, 33−41.

(26) Elford, D.; Lancaster, S. J.; Jones, G. A. Exploring the Effect of Augmented Reality on Cognitive Load, Attitude, Spatial Ability, and Stereochemical Perception. *J. Sci. Educ Technol. 31.* **2022**, *31*, 322−339.

(27) Xu, X.; Villafane, S.; Lewis, J. College students' attitudes toward chemistry, conceptual knowledge, and achievement: Structural equation model analysis. *Chem. Educ. Res. Pract.* **2013**, *14* (2), 188−200.

(28) Kahveci, A. Assessing high school students' attitudes toward chemistry with a shortened semantic differential. *Chem. Educ. Res. Pract.* **2015**, *16* (2), 283−292.

(29) Wu, H. K.; Shah, P. Exploring visuospatial thinking in chemistry learning. *Sci. Educ.* **2004**, *88*, 465−492.

(30) Schulmeister, R. Interaktivität in Multimediaanwendungen. *e-teaching.org* **2005**, 1.

(31) Huwer, J. AG Huwer Forschung Downloads Augmented Reality; https://www.chemie.uni-konstanz.de/ag-huwer/forschung/downloads/augmented-reality/ (accessed on 2024-01-09).

(32) Huwer, J.; Barth, C.; Siol, A.; Eilks, I. Nachhaltigkeitsbildung und Digitalisierung gemeinsam denken − Lernen mit und über den nachhaltigen Einsatz von Tablets am Beispiel einer Augmented Reality Lernumgebung. *CHEMKON* **2021**, *28* (6), 235−240.

(33) Likert, R. A technique for the measurement of attitudes. *Arch. Psychol.* **1932**, *22* (140), 55.