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Using AR to Enhance the Learning of Chirality

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Abstract: This study investigates the use of Augmented Reality (AR) to teach the concept of chirality—a fundamental topic in organic chemistry. Building on Cognitive Load Theory (CLT) and previous research on AR's educational benefits, we designed an AR learning environment to facilitate students' understanding of chirality by allowing them to interact with and superimpose virtual and physical models of chiral molecules. An initial pilot study involving 11th-grade students revealed positive student attitudes towards AR, with participants reporting enhanced comprehension of chirality and a preference for AR-based learning over traditional methods. The follow-up study refined the AR lesson based on pilot feedback, extending its scope to introduce, rather than review, the concept of chirality. Results indicated significant learning gains, low extraneous cognitive load, and high acceptance of AR technology among students. These findings underscore the potential of AR to support complex spatial learning in chemistry, though further research, such as value-added studies, is recommended to explore the generalizability and long-term impacts of AR on different student populations.

Keywords: AR; education technology; organic chemistry; chirality

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1. Introduction

The integration of Augmented Reality (AR) into educational environments has been gaining momentum in recent years, driven by its potential to enhance learning experiences by making abstract and complex concepts more accessible and engaging to students. This trend is reflected in the growing body of research exploring the application of AR across various educational disciplines, particularly in chemistry, where visualization plays a critical role in understanding [1–4]. AR, which overlays digital information onto the physical world, allows students to interact with virtual objects in real time, thus providing a unique opportunity to bridge the gap between theoretical knowledge and practical understanding [5–7].

In chemistry education, AR has been particularly useful in visualizing molecular structures and chemical phenomena that are otherwise invisible to the naked eye [2,8–22]. For example, Abdinejad et al. demonstrated that AR could significantly enhance students' understanding of molecular geometry and bonding by providing 3D visualizations that students can manipulate [1]. Similarly, Fombona-Pascual et al. reviewed 143 studies published between 2018 and 2020, highlighting the widespread adoption of AR in chemistry education to visualize molecules in 3D, thus improving students' spatial reasoning and comprehension of chemical phenomena [2]. Furthermore, in 2022 IUPAC named AR one of the top ten emerging technologies in chemistry, not only for its innovative uses in chemistry research but also in the teaching of chemistry [23].

However, the effectiveness of AR in educational settings is not without its challenges. Cognitive Load Theory (CLT), first developed by Sweller (1988), provides a framework for understanding these challenges by focusing on the cognitive processes involved in learning [24]. According to CLT, learning is most effective when instructional design aligns

with the limitations of working memory, which can only process a limited amount of information at a time [25].

CLT distinguishes between three types of cognitive load: intrinsic, extraneous, and germane [25]. Intrinsic cognitive load is associated with the complexity of the material itself and is influenced by the nature of the content being learned. Extraneous cognitive load refers to the load imposed by the way information is presented. It can be minimized through effective instructional design. Germane cognitive load is the load associated with the process of learning itself, such as the construction of schemas that facilitate understanding and problem-solving.

In the context of AR, while the technology can potentially reduce cognitive load by making abstract concepts more concrete, it can also increase cognitive load if the interface is not user-friendly or if the AR content is poorly integrated into the overall learning experience [25,26]. This has been demonstrated in several studies, where the cognitive benefits of AR were found to be contingent upon careful design that minimizes unnecessary cognitive effort [27–29]. For example, Mazzuco and colleagues found that AR could enhance learning by making abstract concepts more tangible, but poorly designed AR interfaces could overwhelm students, leading to increased extraneous cognitive load that detracts from the learning experience.

In addition to cognitive load, the novelty effect is another concern in the implementation of AR, or any new technology, in education. Holden and Rada adapted the Technology Acceptance Model (TAM) to measure users' acceptance of new technology in educational settings [30]. They noted that new technology could initially capture users' attention due to its novelty. Because it measures parameters that indicate a behavioral intent to use a specific form of technology, the TAM could help reduce the novelty effect on the results of studies of AR in chemistry education [27], as this intent is different from merely having a temporary interest in the novelty of the technology. Keller et al. found that while students responded positively to AR, the long-term effectiveness depended on the alignment of AR activities with learning objectives and the minimizing of distractions [31]. By reducing extraneous cognitive load, AR can be more effectively integrated into learning environments, ensuring that working memory can be more fully used for deep learning.

Despite these challenges, AR continues to show promise in enhancing chemistry education. We have previously shown that AR can be effectively used to teach complex organic chemistry mechanisms, such as electrophilic aromatic substitution and radical substitution [32,33]. The AR learning environments investigated in these studies were designed to facilitate connections between symbolic, macroscopic, and submicroscopic representations [34,35] of chemical reactions and to reduce extraneous cognitive load, ensuring that students could focus on understanding the chemistry rather than grappling with the technology itself.

In 2019, Habig studied students' responses to questions about the chiral configuration of molecules using 2D figures and 3D AR models. He found that the students showed a positive attitude toward using AR in learning about chirality. They found the AR tasks engaging and reported that learning with AR was enjoyable. The study highlighted that both male and female students enjoyed using AR, although no significant gender differences were found in terms of overall attitudes towards AR. The participants also agreed that AR could be a fun and interesting way to learn organic chemistry, particularly in the context of understanding molecular structures. Students generally perceived AR representations as a valuable addition to their learning tools. They believed that AR could help them better understand 3D information, and they expressed interest in learning with AR tools. The students rated the potential of AR positively, with an average agreement that AR representations are a reasonable extension to traditional 2D visualizations and could help in understanding complex spatial information [36]. Although the study found that students generally did not perform better on the questions using 3D AR models, he did find that there was a gender difference, with female students answering the questions correctly more often with 2D figures and male students answering the questions correctly

more often with the 3D AR models. In the following sections, we will show how our study was also designed to investigate impacts on students' attitudes toward using AR to learn about chirality.

In 2022, Elford et al. published the results of their study comparing the use of AR to 2D drawings to teach molecular shape and stereochemistry [37]. They did not find a significant difference between the academic performance of students who learned the topic with AR models versus those who learned with 2D drawings, but they did find that both groups of students performed significantly better on post-tests than pre-tests. Their study also measured cognitive load with the Cognitive Load Scale of Leppnik et al. and found no significant differences between the two groups of students. While they had hypothesized that the students learning with AR would experience lower extraneous cognitive load, this was not the case. Qualitative analysis of student interviews after the lesson revealed that the gamification elements of the learning environment likely contributed to the extraneous cognitive load, offsetting any benefits afforded by the use of AR. The student interviews revealed three predominant themes: supporting the learning experience, augmented reality as an asset, and challenges of integration. Students commented positively on how AR helped them appreciate the three-dimensional nature of chemistry and provided a better understanding of VSEPR concepts. They also mentioned the benefits of AR over traditional methods, such as the convenience and ability to manipulate molecular models. However, some students pointed out the disadvantage of the app only being compatible with newer handheld devices, which left some students without easy access to the AR app [37]. We also designed our study to investigate the cognitive load experienced by students using AR to learn about chirality.

In 2021, Abdinejad et al. found that students who used a 3D AR app to learn about organic chemistry mechanisms had a positive attitude toward using AR to learn this material [1]. Results of a student survey showed that 74% of the participants agreed that the app improved their ability to visualize molecular conformations in 3D, and 77% of students considered it a valuable tool that should be included as a resource along with textbooks. The overall effectiveness of AR in helping students understand chemical concepts was also rated highly, with 72% of students agreeing that the AR images were effective in aiding their comprehension. Furthermore, 73% of students expressed that they would recommend the AR app as a learning tool to other students, indicating a high level of satisfaction with the technology [1]. We incorporated student self-assessment and knowledge pre- and post-tests to investigate learning gains by students who used the AR learning environment to learn about chirality.

The motivation for developing an AR learning environment to teach chirality, a fundamental concept in organic chemistry, stems from the challenges students face in visualizing and understanding three-dimensional molecular structures. Chirality is crucial for understanding stereochemistry, which has significant implications in fields such as pharmacology, where the spatial arrangement of atoms in molecules can determine a drug's effectiveness and safety. Traditionally, students are taught that if a molecule cannot be superimposed on its mirror image, it is a chiral molecule. Conversely, a molecule that is superimposable on its mirror image is nonchiral. While using physical models or two-dimensional representations may be effective for demonstrating chirality in the simplest molecules, students struggle to use these tools to analyze larger chiral molecules, leading to gaps in student understanding and, very often, frustration.

This AR learning environment was designed to facilitate the active construction of knowledge by enabling students to manipulate and interact with digital and haptic models of chiral molecules simultaneously. This interactivity was intended to facilitate their understanding of chirality by allowing them to actually superimpose haptic molecular models over AR models to determine if the two models represent enantiomers, diastereomers, or identical molecules. This type of superimposing of AR models and haptic models to teach chirality has not, to our knowledge, been studied before. This exercise is trivial with the simplest molecules, but quickly becomes challenging with larger molecules that have

multiple chiral centers. In such cases, 2D renderings or even haptic models, which do not allow for true superimposability, present difficulties for students.

We designed a pilot study to evaluate the feasibility of using AR to teach chirality and to gather preliminary data on its effectiveness in improving students' conceptual understanding. The study involved a series of tasks in which students used AR to explore the properties of chiral molecules, comparing these digital models with physical models to reinforce their learning. Initial findings suggested that students accepted the use of AR to review the concept of chirality and even indicated that they would have preferred to have learned about chirality initially with the AR learning environment. Furthermore, students felt that they understood chirality better after using AR to review it. However, the pilot study also revealed the desire on the part of the students for a more structured lesson with more frequent instructions.

Building on these findings, the follow-up study extends the scope of the pilot study by redesigning the lesson and the tasks so that they are suitable for the introduction of the concept of chirality. This follow-up study aims to confirm the initial findings and to investigate students' learning gains and understanding of chirality. The AR learning environment was refined based on feedback from the pilot study, with improvements made to the instructional design to better align with educational goals and reduce extraneous cognitive load.

In the following sections, we will discuss the methodology, results, and implications of these studies, first for the pilot study, and then for the follow-up study. We provide a detailed analysis of how AR can be integrated into chemistry lessons to improve students' understanding of complex concepts such as chirality.

2. Pilot Study

2.1. AR Model Development

The development of the AR learning environment was a key component of the pilot study, aiming to create a simple and interactive tool that could effectively help students learn the concept of chirality. The AR models were developed using the Reality Composer app on iPads, chosen for its ease of use and compatibility with the existing technology infrastructure in schools (iPads and iPhones with iOS 12 or later). The models were designed to closely replicate physical molecular models built using the Cornelsen Experimenta molecular kit, ensuring a high level of congruence between the AR and physical models.

Each AR model was purposefully constructed to maintain the geometric accuracy and color coding of the physical models, crucial for minimizing extraneous cognitive load experienced by the students. For instance, the AR models of chiral molecules such as L-Ribose and D-Ribose were created by modifying a base model, ensuring that every detail, including the orientation of atoms and bonds, matched exactly. This level of detail was necessary to allow students to perform tasks such as comparing enantiomers and diastereomers directly in the AR environment, reinforcing their understanding of molecular symmetry and chirality.

In addition to building the AR models, the development team prioritized the usability and accessibility of the technology. The AR models were made available as reality files that could be easily shared with students through the school's course management platform (e.g., Moodle or Teams) or via AirDrop. This allowed students to download and interact with the models on their devices with minimal technical barriers, ensuring that the focus remained on learning rather than on navigating the technology.

2.2. Collaboration with Teachers in Lesson Development for the Pilot Study

The process of developing the lesson was a collaborative effort that involved close cooperation between the research team and a group of experienced chemistry teachers from the Zentrum für Schulqualität und Lehrerbildung (ZSL) Baden-Württemberg. This collaboration followed the principles of Participatory Action Research (PAR), which em-

phasizes the active involvement of practitioners in the development of educational tools and methods [38,39].

For the pilot study, the lesson on chirality was designed as a review session for 11th-grade students in both basic and advanced chemistry courses. The teachers brought invaluable insights from their classroom experiences, which informed the design and content of the lesson. They emphasized the importance of aligning the lesson with the state curriculum [40], ensuring that the lesson would meet educational standards and learning objectives.

In this study, we, in collaboration with a Participatory Action Research (PAR) group of expert high school chemistry teachers, sought to address a specific challenge in chemistry instruction: the concept of chirality. Chirality is a fundamental aspect of chemistry education and has significant implications in everyday life, as many biomolecules and their functions are inherently dependent on the specific "enantiomer" present. Well-known examples include "L" amino acids and "D" carbohydrates. The determination of whether a molecule is in the D- or L-form is based on its three-dimensional structure, specifically the spatial arrangement of "functional groups" around a "chiral center". To assess the configuration of these functional groups, one must compare possible three-dimensional arrangements. The guiding principle is that substances that are completely "superimposable" are identical, whereas substances that are not superimposable but differ solely in their three-dimensional arrangement are "chiral" to one another and possess distinct properties.

However, traditional approaches to teaching this concept in the classroom present several challenges. Even simple molecules can be difficult for students to conceptualize mentally in three dimensions, necessitating the use of tactile molecular kits. The primary issues with these kits are twofold: first, they are often not available in sufficient quantities due to their high cost; second, assembling larger molecules such as D-glucose is problematic, as the models are prone to disassembly, which can be time-consuming to correct. While the first two challenges could theoretically be mitigated with additional resources, the third and most significant issue requires a technological solution: physical models cannot be perfectly superimposed but can only be positioned adjacent to each other for comparison.

Our approach addresses these challenges by integrating Augmented Reality (AR) technology into the learning process. One molecule is represented physically, while its chiral counterpart is projected three-dimensionally into the physical space through AR. This method effectively resolves these issues:

1. It reduces the need for physical kits by half.
2. It minimizes the handling of the physical model, thereby reducing the likelihood of it falling apart and the time required for assembly.
3. It allows for the actual superimposition of both models, enhancing the accuracy of comparison.

Our conceptual framework ensures that the virtual 3D model closely resembles its physical counterpart, facilitating the seamless integration of virtuality and reality for the learner. An example of the interface can be seen in Figure 1.

The development process began with the creation of a detailed lesson plan, which was then iteratively refined through feedback sessions with the teachers. The lesson plan was structured to include hands-on activities using both physical and AR models and a questionnaire. The teachers played a crucial role in shaping these activities, particularly in ensuring that the tasks were appropriate for the students' level and that the learning process would be scaffolded effectively. The worksheet was designed to guide students through a series of tasks that progressively built their understanding of chirality. It included exercises such as identifying chiral centers in molecules and comparing enantiomers and diastereomers. For example, a student could build a haptic model of D-glucose using the model kit and compare it to the AR model to verify if it was built correctly (see Figure 2 below).

Figure 1. A tablet screen showing a haptic molecular model of a simple molecule and an AR model of its enantiomer. For these models, the colors represent elements as follows: Black, Carbon; White, Hydrogen; Green, Chlorine; Orange, Bromine; Blue, Iodine.

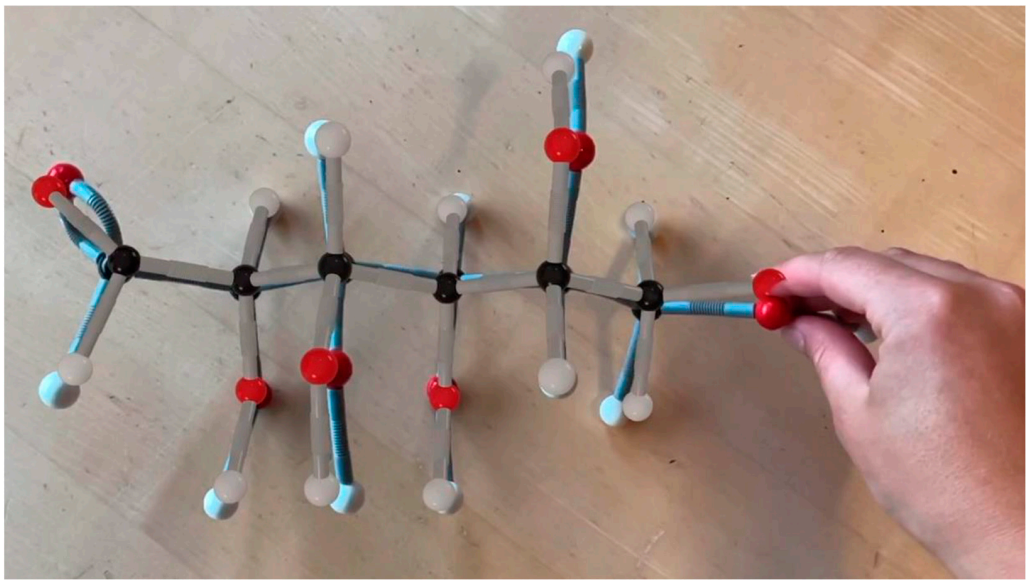

Figure 2. A person overlaying an AR model of D-glucose on a haptic model of D-glucose.

To support students during these tasks, the worksheet included visual aids and definitions, such as the "wedge-dash notation" and explanations of key terms such as "enantiomers" and "diastereomers". These aids were drawn from standard chemistry textbooks in Germany [41] and were presented in an integrated way that minimized cognitive load, in keeping with Cognitive Load Theory [24].

Throughout the development process, the teachers provided ongoing feedback, which was critical in refining both the AR models and the lesson materials. For example, teachers recommended adjustments to the worksheet tasks to include a sequence of activities that built upon each other, along with some additional, more demanding tasks to ensure the core of the lesson would be achievable for all students, yet still stimulating enough for the most advanced learners. This iterative process of development and feedback was essential in

creating a lesson that was both educationally effective and practically feasible for classroom implementation.

2.3. Methods for the Pilot Study

2.3.1. Instruments

To test this AR learning environment, a self-assessment questionnaire for the students was designed, which included questions from validated instruments as well as some simple self-assessment questions we wrote specifically for this pilot study. We wrote the first two questions to prompt students to assess their current level of understanding of the concept of chirality, using a 7-point Likert scale. Students were instructed to answer the first of these two questions before the chirality review lesson and the second one after the review lesson. We wrote a third question, again using the 7-point Likert scale, asking whether they would have liked to have learned chirality initially using this AR learning environment.

The self-assessment questionnaire also addressed cognitive load, user-friendliness, and attitude toward AR in this lesson using a 7-point Likert scale. Items were divided into categories: cognitive load, which included questions on intrinsic cognitive load (ICL), extraneous cognitive load (ECL), three germane cognitive load (GCL), user-friendliness (from the TAM), and attitude toward the use of AR in the lesson. These questions were taken from three instruments that had previously been designed and tested specifically for this purpose: an instrument for measuring the different types of cognitive load experienced by students [42], a version of the TAM modified by Holden and Rada for use in educational settings [30] which we translated into German [32], and an instrument for measuring student attitudes toward the use of AR for learning a topic [43]. These instruments are reported in the literature, and we have used them before to evaluate AR learning environments. Because of limited time with the students during the pilot study, only the questions from the TAM dealing with perceived ease of use (PEU) and usability (U) were included, because these factors are the ones that directly impact behavioral intent when using a technology.

2.3.2. Setting and Participants

The pilot study was conducted in four 11th-grade chemistry classes at four different high schools in Baden-Württemberg, Germany. The lesson focused on chirality as part of the broader curriculum on natural substances, aligning with the state's educational standards [40]. The session was the first hour of a double lesson, of which the second hour was devoted to using AR to review Fischer projections (not addressed in this article). The session began with a brief 10-min introduction to the research project and its goals, followed by a brief overview of chirality. Following this introduction, students assessed their own understanding of chirality before they started the assignment. Then, for thirty minutes, they worked in pairs on a worksheet that included tasks designed to help them identify chiral centers in molecules and understand the concept of chirality using both physical and AR models. Afterward, students had 20 min to complete questionnaires and assessed their own understanding of chirality and their experience using the AR models.

The teaching materials included detailed worksheets that provided definitions, explanations, and visual aids to support student learning. The AR models were made available on each school's local course management platform, which students could access using school-provided iPads on the school network.

2.3.3. Data Collection and Analysis

Before the lesson began, students were asked to assess their current level of understanding of the concept of chirality, using a 7-point Likert scale. At the end of the lesson, students were asked to complete the rest of the questionnaire.

The data were analyzed to answer the following research questions and to test the corresponding hypotheses:

RQ1: *Do the students feel that they know more about chirality after having reviewed it with the AR learning environment?*

H1: *Students' self-assessments of their understanding of chirality after the review activity will be significantly higher than their self-assessments before the review activity.*

RQ2: *What is the extent of the cognitive load experienced by students when working with this AR learning environment?*

H2: *Students will report an experience of low extraneous cognitive load working with this AR learning environment.*

RQ3: *How was the usability of the AR learning environment perceived by the students?*

H3: *Students will respond positively to questions about the usability of the AR learning environment.*

RQ4: *Will the students have a positive attitude toward the use of AR to teach chirality?*

H4: *Students will respond positively to questions about their attitude toward the use of the AR learning environment to learn about chirality.*

2.4. Results of the Pilot Study

We analyzed students' responses to the questionnaire, which included questions to measure cognitive load, AR usability (from the TAM), and student attitudes toward the use of AR for this chemistry lesson. Questions dealing with cognitive load (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. The 7-point Likert scale, which was used for all items in the questionnaire, had a score of 4 as a neutral response, a score of 1 as "strongly disagree", and a score of 7 as "strongly agree". A composite score was calculated for each section of the questionnaire dealing with TAM usability 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 [44]. 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 score. 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. The before and after self-assessment scores were compared with a paired samples *t*-test.

2.4.1. Results for RQ1: Do the Students Feel That They Know More About Chirality After Having Reviewed It with the AR Learning Environment?

Students reported, on average, that they felt they had a better understanding of chirality after working with the AR lesson than they had before. The average of the self-assessment scores for understanding chirality before the AR review lesson was 4.2, while the average of the scores reported after the lesson was 5.5. The standard deviation for the scores before the lesson was 1.4, whereas the standard deviation for scores after the lesson was 1.2. The distribution of the scores is visualized in the boxplots in Figure 3.

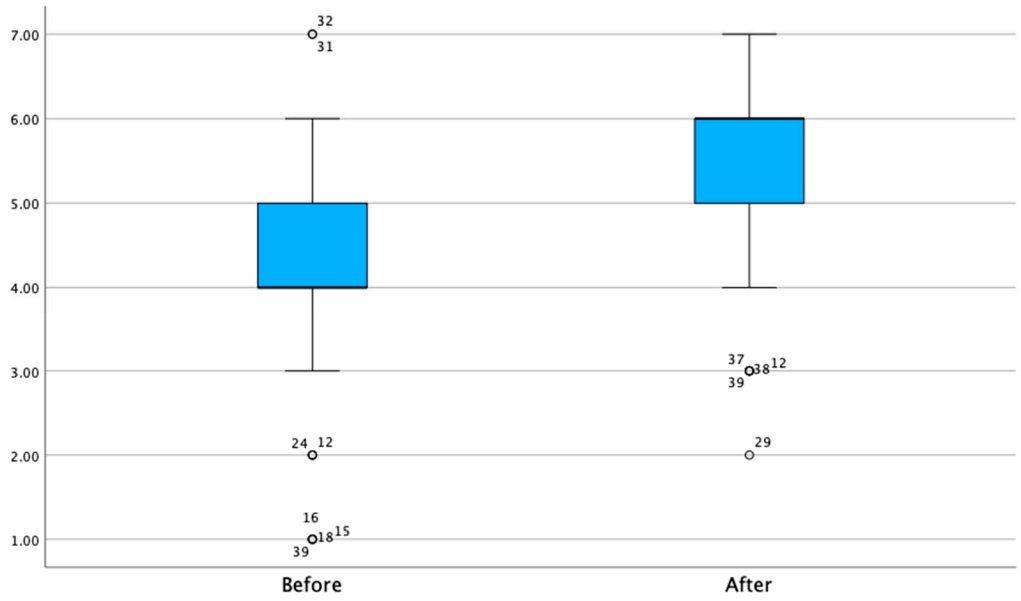

Figure 3. Boxplots for the before and after scores of students assessing their understanding of chirality.

A paired samples *t*-test showed that there was a statistically significant difference between the before and after scores (M = 1.30, SD = 1.15), t(52) = 8.218, $p < 0.001$. The 99% confidence interval for the mean difference was between 0.88 and 1.73, indicating a significant improvement in students' perceived understanding of the concept following the AR intervention. We, therefore, confirm H1.

2.4.2. Results for RQ2: What Is the Extent of the Cognitive Load Experienced by Students When Working with This AR Learning Environment?

The results of the individual questions for the assessment of cognitive load can be seen in the boxplots in Figure 4.

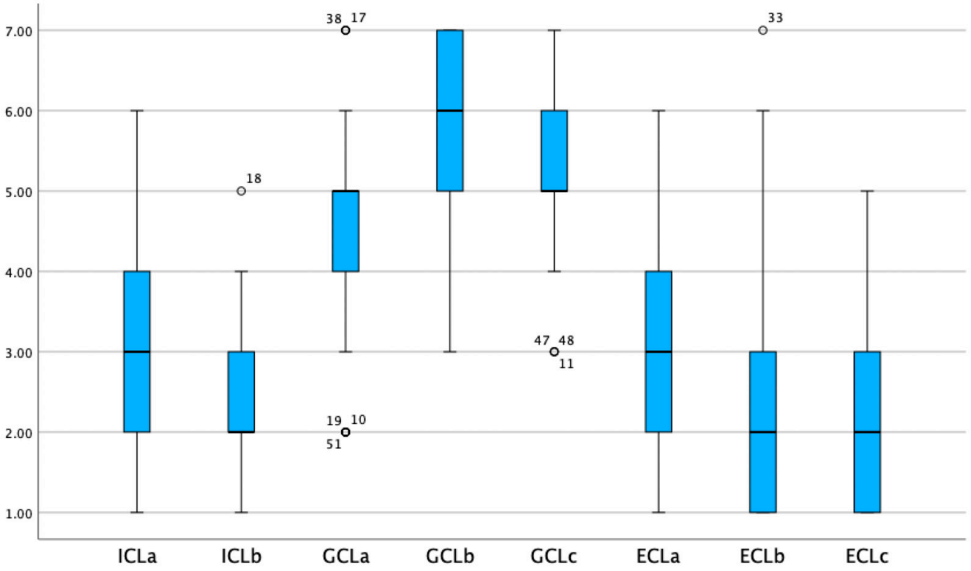

Figure 4. Box plot for composite scores for CL questions, showing the extent to which students experienced the different types of CL. A score of 7 is the highest rating, a score of 1 is the lowest rating, and a score of 4 is a neutral rating.

The scores show that, generally, students experienced low intrinsic cognitive load (ICL) and extraneous cognitive load (ECL) but comparatively high germane cognitive load (GCL). While the distribution of scores for ECL is broad, the median for all three scores is 3 or below. These results confirm H2.

2.4.3. Results for RQ3: How Was the Usability of the AR Learning Environment Perceived by the Students? And for RQ4: Will the Students Have a Positive Attitude Toward the Use of AR to Teach Chirality?

Regarding the usability of the AR environment and the attitude of the students toward using AR in this chemistry lesson, the results were positive. The average composite score for usability was 5.7, and for attitude toward the use of AR in this chemistry lesson, the average score was 5.5. The responses to the question about whether students would have preferred to use AR to learn about chirality originally had an average of 5.3. The distributions of these scores are visualized in the boxplots in Figure 5.

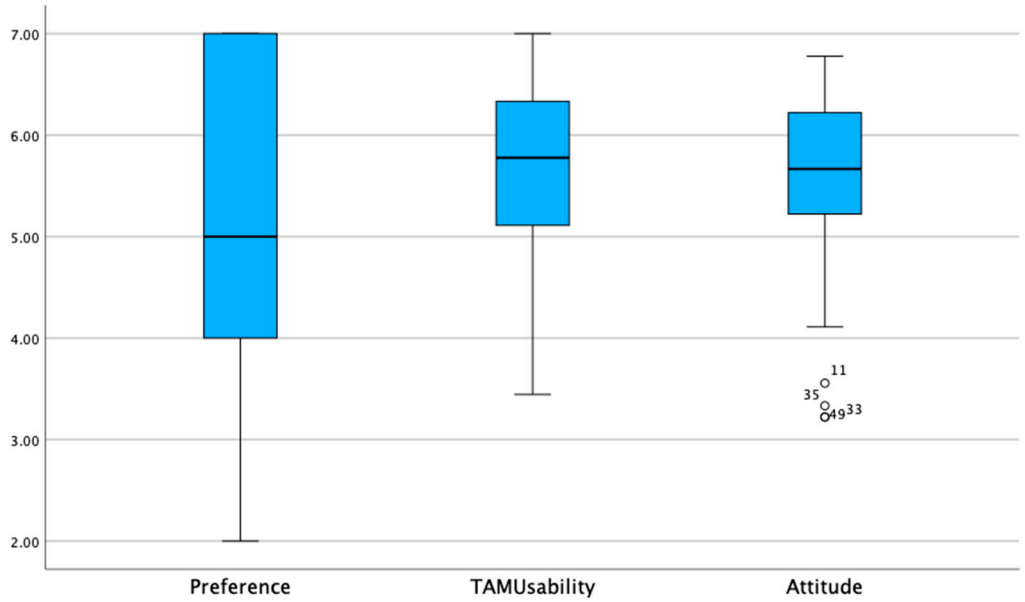

Figure 5. Boxplots for the composite scores of students assessing their preference for using AR to learn about chirality initially, the usability of the AR learning environment (from the TAM), and their attitude toward using AR in this chemistry lesson.

A large majority of students (71%) indicated that they would have liked to use AR for their initial chirality lessons. Feedback from students in the free response questions at the end of the questionnaire highlighted the intuitive usability of the AR models, with many noting that the ability to rotate and examine molecules from different angles provided a clearer understanding of the concept than traditional 2D representations or physical models alone. The results of the major themes found in these responses can be seen in Figure 6. The students' responses to these questions indicate that H3 and H4 are confirmed.

Theme (What did you like?)	Number
Good help through increased clarity and help in presenting the models	29
Easy handling, application and intuitive operation	14
Innovative, different way of learning	3
Independent learning	3
Time saving	3
Theme (What can we improve?)	**Number**
More features (mirroring, inserting layers, rotating in 3D or building models) for more independent work	11
Clearer task definition	6
Introduce AR better (with more explanation, hints or examples)	5
2D or 3D models sufficient compared to AR	4

Figure 6. The most frequently recurring themes in the open-ended questions from the student questionnaire in the pilot study.

2.5. Discussion of the Pilot Study

The statistically significant increase in the students' self-assessment of their understanding of chirality before and after the review lesson with the AR indicates that the students found it helpful in their review of chirality. Regarding cognitive load, the results show consistently high GCL and low ICL and ECL. The consistently positive responses from the students regarding the usability of the AR and their attitude towards using it in the chirality lesson indicate that they accept it as a learning technology. Furthermore, a large majority of students would have preferred to have learned about chirality initially with this AR learning environment.

We concluded that these results warranted the further development of this AR learning environment as a tool for introducing the concept of chirality to 11th-grade students.

3. Follow-Up Study

After testing the AR-enhanced lesson for the pilot study in the summer of 2023, valuable feedback from both students and teachers was used to enhance the lesson plan and develop a new worksheet, while using the same AR models, to introduce the concept of chirality.

The new lesson was necessarily longer than the pilot lesson since it was used to introduce, rather than review, chirality. The new worksheet provided more detailed step-by-step instructions, addressing the students' difficulties in getting started with the AR learning environment. This aimed to offer a more structured approach, helping students navigate the AR tools with greater ease and focus on the chemistry content rather than the mechanics of the tools.

The follow-up study's worksheet incorporated guided comparisons and hypothesis development exercises. While the review activity for chirality in the pilot study included only brief instructions for students to build the molecules shown on the worksheet and compare them with the AR models provided, the activity for the introduction of chirality in the fall included specific step-by-step instructions on how to build the molecules shown, how to find the correct AR file, and what precisely to look for when comparing the built models to the AR models. In the introductory activity in the follow-up study, each task on the worksheet was broken into discrete steps with detailed instructions, especially when telling the students what to look for: "Compare your molecule models with the mirrored AR molecule models on the iPad. Check them for chirality by trying to "place"

the AR molecule models directly onto the model you have built. Represent the mirrored AR molecule in wedge-dash notation. Represent the mirrored AR molecule in wedge-dash notation. Label the asymmetric C* atoms and make a reasoned decision as to whether the molecules are chiral to each other. Check them for chirality, as you did in task 1". In the introductory activity, students were also asked to propose hypotheses for the cause of the chirality of the molecules as they interacted with the AR models.

These tasks, which included labeling asymmetric carbon atoms and forming hypotheses about chirality, were designed to reduce cognitive load by allowing students to build their understanding incrementally.

The worksheet encouraged students to self-check their work using AR models, embedding independent learning into the chemistry curriculum and promoting process-related competencies.

The primary objective of the follow-up study was to adapt the lesson plan used in the pilot study to introduce the topic of chirality rather than to review it, as was done previously. A key focus of the follow-up study was to ensure that the extraneous cognitive load experienced by students remained low or was reduced compared to the pilot study. Additionally, the study aimed to address the feedback from students in the pilot study, who requested more structure in the assignment. Whereas the lesson for the pilot study consisted entirely of students working in pairs to complete a review activity, the lesson plan for the follow-up study was much more structured and intended to provide a solid introduction to the concept of chirality and the skill of determining whether molecules were identical or enantiomers.

The lesson began with a typical introduction of chirality by having students compare their own hands to see how they might seem identical, but that they are actually non-superimposable mirror images of each other. The students had the chance to view everyday objects in a mirror to see if the mirror images would be superimposable on the real objects. Here is where chirality and achirality were defined. At this point, the worksheets with the structured activity were distributed, and students worked in pairs, building models of simple molecules and comparing them to the AR models. Students were asked to hypothesize the cause of chirality in the chiral molecules, based on what they had just learned and what they had observed. Then students moved on to investigate more complex molecules and learn the naming system for aldoses. After a class discussion of the results, the students moved on to a practice phase involving more complex molecules. Additional tasks were available for students who were ready to explore further.

3.1. Methods for the Follow-Up Study

3.1.1. Instruments

To test this AR learning environment, we used a longer self-assessment questionnaire than the one used in the pilot study. It included the same questions about cognitive load [42] and attitude toward the use of AR in the lesson [43], but it also included all of the questions from the TAM [30] which we had translated into German [32]. To measure learning gain, we used pre- and post-tests, which were designed in collaboration with the teachers and were graded with a binary rubric.

3.1.2. Setting and Participants

The follow-up study involved a smaller student population than the pilot study, consisting of 32 eleventh-grade students from mid-sized public schools in Baden-Wuerttemberg, Germany. These students completed the self-assessment questionnaires, while 28 students completed the pre- and post-tests designed to measure learning gains. The study took place in three different schools; one of these schools had also participated in the pilot study, while the other two were new to the project. Despite the different locations, all schools were similar in that they were mid-sized public institutions following the same state-wide curriculum, ensuring a consistent educational context across the studies.

3.1.3. Data Collection

Before the lesson began, students took the pre-test. The self-assessment questionnaires were distributed to students at the end of the lesson, completed as homework, and returned in the next class session. Teachers administered the post-tests to the students within one week of the lesson.

The data were analyzed to answer the following research questions and to test the corresponding hypotheses:

RQ1: *Does the use of this AR learning environment help students learn the concept of chirality?*

H1: *Students' scores on the post-test will be significantly higher than their scores on the pre-test.*

RQ2: *What is the extent of the cognitive load experienced by students when working with this AR learning environment?*

H2: *Students will report an experience of low extraneous cognitive load working with this AR learning environment.*

RQ3: *What is the extent of student technology acceptance when working with this AR learning environment?*

H3: *Students' responses will be positive and therefore indicate acceptance of the AR learning environment.*

RQ4: *Will the students have a positive attitude toward the use of AR to teach chirality?*

H4: *Students will respond positively to questions about their attitude toward the use of the AR learning environment to learn about chirality.*

3.2. Results of the Follow-Up Study

3.2.1. Results for RQ1: Does the Use of This AR Learning Environment Help Students Learn the Concept of Chirality?

The follow-up study yielded several positive results. There was a statistically significant learning gain, as seen in the comparison of pre- and post-test scores. The students' scores on the post-test were significantly better than their scores on the pre-test ($Z = 4.643$, $p < 0.001$). Boxplots visualizing the distribution of the scores can be seen in Figure 7. These results lead us to confirm H1.

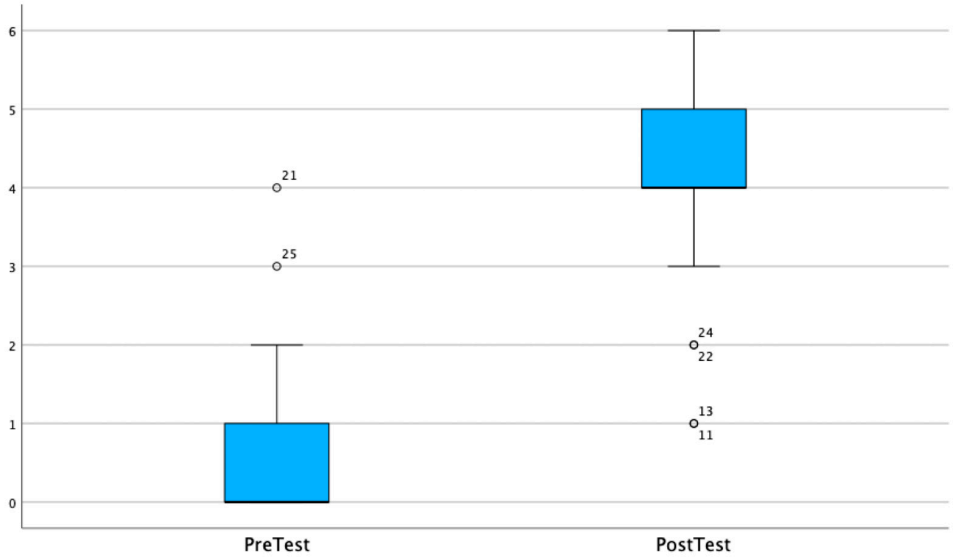

Figure 7. Boxplots showing the distribution of pre- and post-test scores from the follow-up study.

3.2.2. Results for RQ2: What Is the Extent of the Cognitive Load Experienced by Students When Working with This AR Learning Environment?

Students experienced high GCL and low ECL, but the results for ICL were mixed. A closer look at the ECL scores shows that the median scores for all three ECL questions were at 3 or below. Seventy-five percent of the responses for the first ECL question were at 3 or below, whereas all the responses for ECL questions 2 and 3, except for statistical outliers, were at or below 3. The boxplots visualizing the results of the cognitive load assessment can be seen in Figure 8. We can confirm H2, in that students experienced low ECL while working in the AR learning environment.

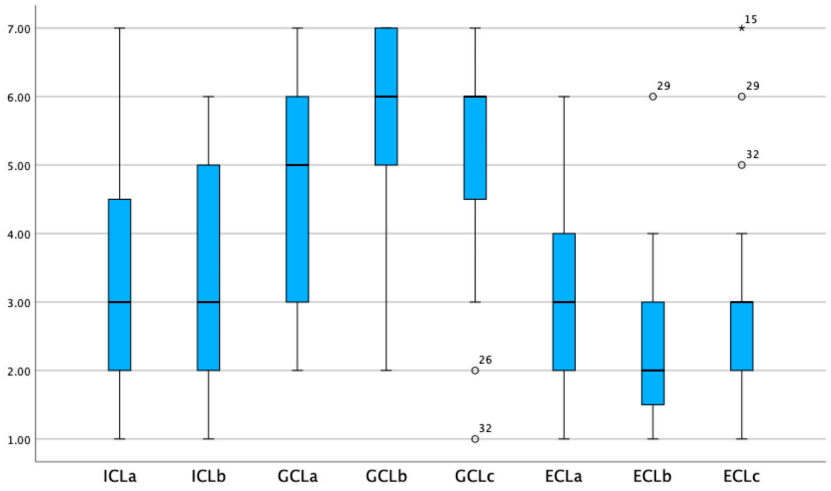

Figure 8. Boxplots showing the distribution of cognitive load scores from the follow-up study.

3.2.3. Results for RQ3: What Is the Extent of Student Technology Acceptance When Working with This AR Learning Environment? and for RQ4: Will the Students Have a Positive Attitude Toward the Use of AR to Teach Chirality?

Students also reported high acceptance of the AR technology and a favorable attitude toward using AR to learn chirality. Figure 9 shows the results of the questions regarding technology acceptance (from the TAM) and the attitude of the students toward using AR in this chemistry lesson.

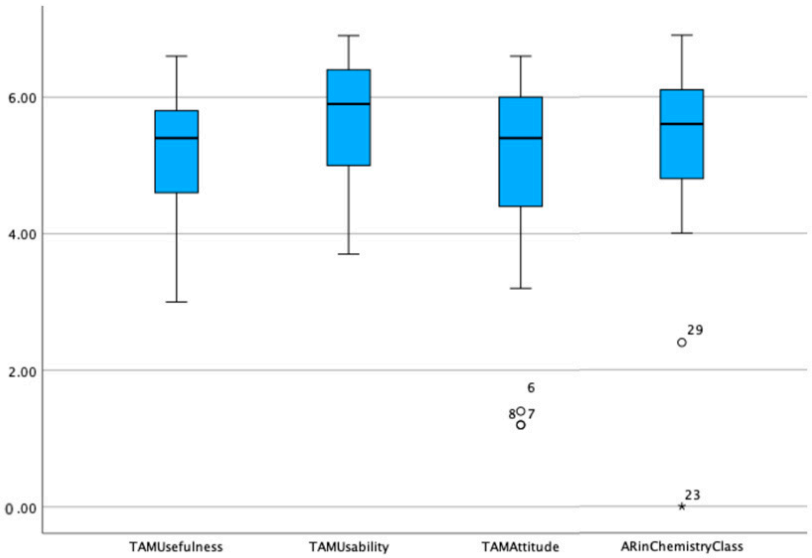

Figure 9. Boxplots showing the distribution of scores from the three sections of the TAM questions, as well as the questions about the students' attitudes toward using AR in the follow-up study lesson.

An analysis of the students' responses to the open-ended questions at the end of the questionnaire revealed an overall positive view of the AR learning environment. A breakdown of the most frequently recurring themes in those responses can be seen in Figure 10. The students' responses to the questions about technology acceptance and attitude toward using AR to learn chirality indicate that both H3 and H4 can be confirmed.

Theme (What did you like?)	Number
Helpful, more clear, easier to understand	15
New/Interesting/Different/Fun/Motivating	7
3D visualization	7
Independent learning/good strategy for learning	5
Theme (What can we improve?)	**Number**
Slow loading of AR files/difficulty scaling or rotating AR models	9
Android version	2
Nothing	2
Use it more often in chemistry class	1

Figure 10. The most frequently recurring themes in the open-ended questions from the student questionnaire in the follow-up study.

3.3. Discussion of the Follow-Up Study

The follow-up study confirmed the effectiveness of the AR learning environment in teaching chirality to 11th-grade students. The results showed that the adaptations made to the lesson plan successfully maintained the positive reception and low extraneous cognitive load observed in the pilot study, while also contributing to significant learning gains. The structured approach and additional support provided in the follow-up study likely played a role in these outcomes.

When comparing the follow-up study with the pilot study, there were no statistically significant differences in the extraneous cognitive load experienced by students or in their responses to the technology acceptance survey. This indicates that the lesson plan in the follow-up study was as well-received as in the pilot study, with a similarly low extraneous cognitive load. Although the follow-up study did not achieve a lower extraneous cognitive load as hoped, the consistency with the pilot study's low levels was considered a positive outcome. Given the more highly structured and detailed nature of the tasks in the follow-up study, a lower ECL than that seen in the pilot study was expected.

While the follow-up study did not achieve a further reduction in extraneous cognitive load beyond that of the pilot study, the findings suggest that the AR environment is effective for both reviewing and introducing the concept of chirality to 11th-grade students. The follow-up study highlights the importance of continuous feedback and iteration in the development of educational tools, particularly when integrating new technologies into the classroom. Furthermore, our findings are consistent with the results of other studies on the use of AR to teach complex chemical concepts that depend on 3D visualization.

Our study also showed positive attitudes toward the AR learning environment on the part of the students and are, in this way, consistent with Habig's findings [36]. We did not compare our AR learning environment to 2D diagrams, nor did we look for any gender differences, so we cannot comment on any further consistencies or contradictions between these two studies.

While we did not compare our AR learning environment to 2D diagrams, our findings of a significant increase in post-test scores over pre-test scores are consistent with the results of Elford et al. in 2022 [37]. Both studies hypothesized a lower ECL for students using AR to learn complex chemical concepts. We cannot compare the absolute values measured for ECL, since different validated instruments were used in the two studies. It seems that the inclusion of gamification elements in the AR learning environment studied by Elford et al. in 2022 could be the reason that they did not observe lower ECL reported by students using AR to learn complex chemical concepts. The results of both studies indicate that students had a positive attitude toward the use of AR to learn these complex chemical concepts.

The findings our study are consistent with the results from Abdinejad's study [1]; our participants also reported a positive experience with the AR learning environment and felt that it helped them visualize the 3D configurations of the molecules better.

4. Conclusions

As with previous studies, we found that AR is helpful in teaching a complex chemical concept [1,28,29,32,33,36,37], in our case, the concept of chirality, and that students have generally positive attitudes toward the use of AR to learn about it. Specifically, our results indicate that our AR learning environments can be used effectively as a review tool and as an introductory tool for the concept of chirality. The introduction to chirality lesson using this AR learning environment could be improved with a few simple modifications. First of all, the AR models could all be uploaded onto the individual iPads so that there is no need to depend on the Wi-Fi network to interact with the models. This would make it easier for the students to interact with the models. Secondly, teachers at schools that use Android devices could convert the AR models into file formats such as GLB, which are compatible with Android devices.

Other modifications would be more labor intensive and would require more preparation on the part of the teacher. Students in our pilot study and follow-up study expressed interest in building models themselves. It is not easy to construct models in Reality Composer with appropriate angles, so building proper models can be very time-consuming. This problem could be minimized by building a few small, commonly used pieces with the proper angles and then duplicating those, effectively creating an AR modeling kit. Students could more quickly assemble these pieces into any molecule they needed, after a bit of instruction on how to use Reality Composer. This modification would allow for more active engagement on the part of the students but would increase the extraneous cognitive load for the students.

To further investigate our claim that this AR learning environment can be used effectively as a tool to review or introduce the concept of chirality, a controlled value-added study, as described by Buchner and Kerres in 2023, should be carried out in future work. In their 2023 review, Buchner and Kerres show that the vast majority of the research into the use of AR in education are media comparison studies, which, they claim, are of limited value. Such studies are considered technology-centered [45] and are designed with the instructional media as the independent variable. Unfortunately, this type of study is inherently flawed [46,47], does not control for other relevant variables, and does not replicate in other settings [48]. If such studies are included in a meta-analysis, then the results of the meta-analysis are similarly flawed [49].

Therefore, Buchner and Kerres advocate for learner-centered studies instead, which can be considered in two types: value-added or learner-treatment-interaction (LTI) studies. An empirical investigation that compares the same technology by manipulating a feature within it would be considered a value-added study. Using an AR learning environment with two different instructional methods would also qualify as a value-added study. On the other hand, LTI studies investigate the attributes of the learners as factors that affect the learning process with the technology. Using an AR learning environment with advanced students and regular-track students would be considered an LTI study, for example. Such studies are more useful to practitioners and researchers than media comparison studies

because they are learner-centered approaches [45] that shed light on questions about when and how learning with a specific technology works best.

Other future studies could include using the AR learning environment, both to introduce the concept of chirality and to review it later in the course. Such a study would present the opportunity to test for long-term retention of the concept.

5. Limitations

We carried out this project within a Participatory Action Research framework, so our sample population was limited to the number of teachers participating in the project. As is the case with many similar studies, the relatively small sample size is a limitation to the generalizability of the results. However, a more problematic limitation of this study is that it may be difficult to generalize the results to student populations other than high school students who are learning organic chemistry. For example, the concept of chirality is not taught in most high school chemistry courses in the US, but rather taught at the university level to older and more advanced students. While it may be logical to expect similar results from, for example, US university students learning about chirality, it cannot be assumed that the effects will be the same. Older students may have different capacities for cognitive load than their less mature counterparts, for example, which would likely affect the results.

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Institutional Review Board Statement: All participants were students at German schools. They took part voluntarily and were told that they could quit participating at any time. The anonymity of participants was guaranteed during the study. Due to all these measures in the implementation of the study, an audit by an ethics committee was waived.

Informed Consent Statement: Informed consent was obtained from all participants involved in the study, or, in the case of minors, obtained from their parents.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and ethical restrictions.

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