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Interactive Learning with iPads and Augmented Reality: A Sustainability-Oriented Approach to Teaching Plastics Chemistry

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Abstract: As the use of handheld devices continues to proliferate in both private and educational sectors, critical questions emerge concerning the end-of-life management of materials and strategies to curtail waste generation. Augmented reality (AR) technology presents novel avenues for engaging students in science education. This paper presents a novel didactic methodology through a tablet-based, digitally enriched learning scenario that focuses on the properties, synthesis, substitution, and recycling of plastics, particularly in the context of iPads. The scenario utilizes AR technology to provide new perspectives on plastics' chemistry, fostering interest and understanding. Additionally, the present study employs quantitative methods to investigate the impact on situational interest and understanding concerning learning with iPads and learning about plastics used in iPads on students. The analysis also includes an examination of attitudes toward learning experiences based on AR. A total of 65 secondary students participated in the study. The findings contribute to the ongoing debate on context-based learning and its impact on students' interest and engagement in science education.

Keywords: chemistry education; augmented reality; plastics; learning; interest

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1. Introduction

The widespread acquisition of electronic devices has presented an additional environmental challenge: the management of electronic waste once the devices reach the end of their lifecycle. In 2021, 74% of young people already had access to handheld devices at home, e.g., mobile phones or tablet computers, especially iPads [1]. The relevance of the iPad results from its versatile use and high prevalence [2]. One of the materials used in the iPad is plastic. Therefore, it represents a relevant context for learning about plastics chemistry. In addition to its function as a learning context, the iPad can also be used as a digital learning tool in digitally enriched learning scenarios, e.g., to watch videos or access augmented reality (AR) content [3]. AR is a continuum of reality and virtuality and is defined through 3D registration, merging of real and virtual content, as well as real-time interactivity [4,5].

With iPads in schools, a changed learning culture could come to pass, which is characterized by collaborative, communicative, and student-centered teaching concepts [6]. Furthermore, learning success can be proven using tablets, which, however, is presumably dependent on the digital competencies of the teacher [6]. Through the hardware and software, it is possible to combine reality and virtuality using iPads, which opens up new, cost-effective, school-based uses for augmented learning content. The ability to represent chemical facts at the particle level using AR, and thus bring non-intuitive content closer, can reduce misconceptions on the part of learners, promote their understanding, and thus lead to an increase in performance [7–9]. Insights into devices, such as an iPad and technical equipment that are not normally possible, can also be realized using AR. In addition, enriching analog media with AR and other (multimedia) content, such as videos, graphics, etc., supports the effectiveness of digital teaching–learning materials [10]. Furthermore, AR can be used to create differentiated learning opportunities and thus promote learners' learning growth, perceived self-efficacy, and self-regulation [11–13]. Moreover, it could be shown that AR learning scenarios are able to evoke situational interest and can help simplify understanding [14,15]. As reported by Yu et al. [16], students find AR learning scenarios helpful and effective.

In the project "Rare Earths & Co in Digital Sustainability Education", the focus is explicitly on the materials of the iPad, which is increasingly used by young people in their private lives and the school context [17,18]. The aim is to provide learners with digitally enriched, modular learning environments to give students an insight into the iPad and to address materials used in it as well as the resulting problem of waste. The project's focus on handheld device learning is influenced by three key concepts: relevance in science education [19], socio-critical and problem-oriented science teaching [20], and systems thinking [21]. Therefore, the augmented learning environment engages students to explore tablet sustainability's environmental, social, and economic impacts. Based on the main components of a tablet—battery, circuit board, case, display, and plastics/adhesives—five learning scenarios have been developed for grades 9 to 13. Each scenario covers five areas: disassembly, properties, production/function, recycling, and raw material substitution. Small modules on life cycle analysis are also included. Methodologically, the learning scenarios consist of digitally enriched theory stations (e.g., enhanced interactive elements, explanatory videos, and animations) and two to four experiments. The latter can be carried out physically or digitally so that the learning scenarios can also be used remotely, regardless of location, while avoiding security risks. The time frame (usually 3 h in total) and the thematic focus can be adapted to the learning group due to the modular structure of related subtopics. The sustainable use and effective recycling of the tablet hardware as learning objects are also digitally enriched in terms of methodology and media didactics through learning with the tablet. This dual instrumentalization of the tablet is one of the distinguishing features of the project. In recent years, various augmented learning scenarios have been created within the project, such as neodymium in speaker magnets or lithium-ion batteries, among others. In addition to the subject of chemical content, sustainability aspects, as well as the handling of these materials at the "end of life" of an iPad or their substitution possibilities, are particularly considered [22].

The following paper presents a new didactic approach to how an iPad-related consideration of the properties, production, processing, recycling, and use of plastics, as well as possibilities to replace them, can take place in a tablet-based digitally enriched learning scenario. The use of digital technologies such as AR enables a new perspective on and into the content of plastics chemistry in class. This allows not only the basic content of this subject to be addressed but also areas and perspectives such as highly relevant sustainability aspects of digital devices.

2. Research Questions

The proposed innovative didactic approach allows for the utilization of AR, fostering students' situational interest and understanding of highly relevant sustainability topics related to plastic waste. This strategy aims to capitalize on the reported positive impacts of this technology.

Learning with and about electronic devices, particularly with augmented reality, as well as the issue of sustainability, is reflected in the research questions. This study focuses on understanding and situational interest of students while learning with iPads and learning about iPads. The research questions (RQ) were as follows:

RQ1: What effect does the simultaneous use of iPads as a learning tool and as a learning object have on pupils' understanding of the use of plastic in these devices?
RQ2: What attitude do students have toward learning with AR in chemistry lessons after implementing the AR learning scenario?
RQ3: How does the simultaneous use of iPads as a learning tool and as a learning object affect the students' situational interest regarding the use of plastic in these devices?

3. Sample and Method

3.1. Context and Participants

The intervention took place from the spring to summer of 2023 in Germany. Sixty-five high school students were involved during their chemistry lessons. Three 10th-grade high school classes worked on the learning environment for 9 to 12 school hours, each lasting 45 min. Before teaching, teachers were instructed in a three-hour workshop and accompanied by the research team in the last two lesson periods. The students participated voluntarily in the study, with parental consent obtained for their involvement and for collecting, analyzing, evaluating, and publishing data regarding their perspectives. No personal identifying information was recorded to ensure participant anonymity. The data collection was conducted in German, and the results were later translated into English.

3.2. Data Collection

The study is quantitative. In the laboratory session, which consisted of various sub-topics, specific questionnaire forms were filled out by the students after each sub-topic. The questionnaires were administered immediately after completing each respective sub-topic to ensure that the students' experiences were fresh in their memory. Short questionnaires were used to allow for a time-efficient way to capture the opinions of the students on selected aspects. Not all students were able or willing to complete every questionnaire due to their progress through the learning experience. Data were then analyzed using descriptive statistics in Excel.

3.3. Questionnaire

Each station's questionnaire consisted of 10–12 items that students could rate using a four-point Likert scale [23] using the terms "I agree", "I mostly agree", "I mostly disagree", or "I disagree". To avoid the "ambivalence–indifference problem" [24] (p. 180), a neutral response option was omitted.

The self-assessment for students comprises several items related to their level of interest and perceived understanding, as well as specific questions related to the AR experience at each station, based on the work by Rheinberg, Vollmeyer, and Burns [25]. The selection of this questionnaire was predicated upon its alignment with the context of our study, specifically the computer-based learning environment. The questionnaire's tailored items were adept at eliciting insights into students' levels of interest, perceived comprehension, and engagement with augmented reality (AR) across diverse stations. Furthermore, we opted to refine certain questions to better address the unique demands and objectives of our investigation. Employing this questionnaire facilitated the comprehensive examination of both overarching elements of learning and performance scenarios, as well as specific insights into students' encounters with AR technology. This approach was pivotal in fostering a nuanced comprehension of how AR applications were perceived within our educational milieu and their impact on students' engagement and comprehension. Nevertheless, it is important to recognize that despite these adjustments, the questionnaire may not have fully captured all dimensions and effects of motivation in AR use. Therefore, our statement regarding motivation only refers to the recorded aspects of (current) motivation according to Rheinberg et al. [25]. Two items were dedicated to assessing the students' understanding, which remained consistent across all sub-topics. Two items related to AR were assessed uniformly at all sub-topics. Additionally, each sub-topic included one to two specific items tailored to the content of that particular station. For the sub-topics focusing on properties, production, and substitution, additional specific data related to the respective AR applications were collected. For assessing interest, five items were applied uniformly across five sub-topics. However, in the sub-topic focusing on the structure of iPads, the question about whether one would like to learn more about the properties of plastics was replaced with two specific questions to capture students' perspectives on that particular aspect of the sub-topic.

4. Learning Scenario

The conceived learning scenario was developed to promote students' situational interest and understanding of crucial sustainability issues related to plastic waste—both through the use of tablets as learning tools and subjects and through the integration of AR applications. The learning scenario was developed as part of the project "Rare Earths and Co in Digital Sustainability Education" and is suitable for grades 10 to 13. The learning scenario is divided into five sub-topics with analog, digital, and experimental content that can be worked on independently by learners in groups of two or three in any order. Four of the stations are also enriched with augmented reality learning content, which enables new perspectives on and into the content of plastics chemistry, particularly at the particle level. The contextual basis of the scenario is the consideration of plastics as components of an iPad. Thus, the iPad is not only the learning tool but also the learning object itself. For this purpose, the scenario takes a phenomenological view of plastics, using the particle level to explain corresponding material aspects (including structure–function relationships). The consideration of the symbolic level, according to Johnstone [26], is completely omitted. Therefore, as well as the extension of the topic by aspects of sustainability and criticality, the learning unit is recommended as a supplement to regular chemistry lessons. Individual sub-topics can be selected and worked on as needed. The components of the iPad are discussed, such as the proportion of plastics in the components used, the properties of plastics, the manufacturing processes for plastics, and the possibilities for recycling and substitution. Therefore, before using the material, the definition of plastics and their synthesis pathways at the particle level should have been taught.

4.1. Design and Used Programs

When creating the learning environment, Gestalt principles, according to Böhringer et al. [27], and the principles of multimedia learning (including [28–32]) were taken into account. Maya 2023 software from the developer Autodesk Inc, San Francisco, CA, USA. Was used to create and animate the 3D models. The AR applications were created using the ZapWorks Studio authoring tool from Zappar Ltd., Auchterarder, UK. These applications can be accessed by scanning the Zapcode with the free Zappar app from the same developer. YouTube learning videos were integrated into the learning unit through the learningapps.org website. This website allows excerpts of YouTube videos to be shown and, among other things, prevents other content from being displayed to students. A PowerPoint presentation is provided to visualize content (hints, QR codes, etc.) during the introduction and follow-up. The tool "genial.ly" was used to create further digital, interactive content.

4.2. Introduction

To introduce the learning scenario, students' associations with the colloquial term plastic are collected, for example, as a Wordcloud via the online tools Mentimeter or Answergarden. In addition to examples and properties of plastics, learners are likely to address the negative aspects of plastics released into the environment. This points to the future significance and authenticity of the topic. Following this, learners are asked if and what kind of items made of plastics they carry, highlighting the relevance to all areas of learners' everyday lives. The term critical raw material or criticality is then introduced and briefly explained using an example such as cobalt. The students are then asked to make an initial assessment of whether plastics could be a critical raw material. In the course of this, the central problem question of the learning scenario is presented to the learners by the teacher: “Should plastics be used as materials for iPads (and other things)?”. As a transition to the digital learning environment, the learners receive information about the procedure, time, safety regulations, and material.

4.3. Sub-Topic 1: Construction of an iPad with a Focus on the Plastics Used in the Components

The first sub-topic deals with the assembly of iPads with a special focus on plastics used in the installed parts. In advance, the adhesions were loosened, the lithium-ion battery removed, and screws and plugs colored to facilitate disassembly and assembly, avoid errors, and reduce potential danger. By scanning the QR code, learners can access the digital disassembly/assembly instructions. With these, learners disassemble the iPad and remove the speaker, front camera, and LCD, among other components. Components that the learners cannot remove are available in a separate envelope. Subsequently, learners are prompted to ascertain the relative proportion of plastic in the components. To accomplish this, learners weigh the plastic parts and calculate, utilizing the information available in the AR, the quantity of plastic in grams integrated into an iPad. The disassembled iPad is positioned on the surface with the Zap code to activate the AR, thereby obtaining information on the relative plastic content. Scanning the code activates an image-tracking AR, allowing learners to assign names to the significant visible components of the iPad (Figure 1). You can find this Zap code and image-tacking files, as well as all the following ones, under the Supplementary Materials.

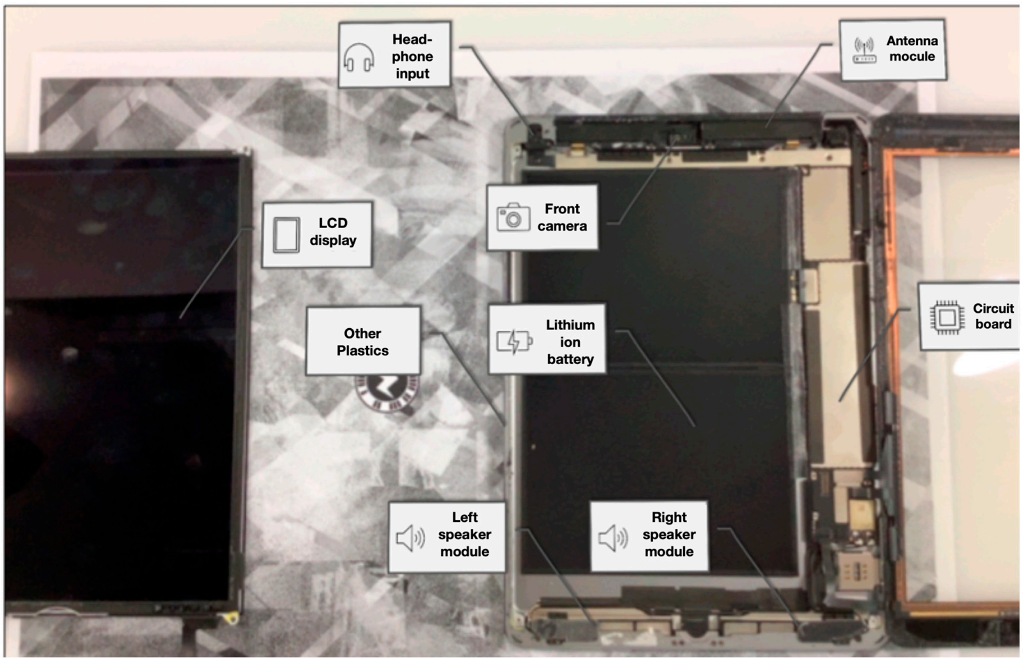

Figure 1. AR for identifying and naming the iPad components in the opened iPad. Clicking on one of the components opens the corresponding short information.

By touching the respective text box, the learners receive a brief description and the relative plastic content of the component (Figure 1). After the learners have calculated the plastic content [g] of the iPad, they reassemble the iPad. Due to its relevance to everyday life and the high reference to the iPad, the learners then deal with the plastic content of an Apple Pencil and the corresponding charging cable. Both objects are available to the learners, among other things, for weighing. However, learners cannot dismantle these, as it can only be realized with considerable additional effort and a higher risk of injury. Instead, disassembly is simulated by a world-tracking AR (Figure 2). By scanning the Zapcode (v2-460-9f4ecc1-dirty), they can place the augmented Apple Pencil in the real world (world tracking) and view it from all sides. You can choose between the Apple Pencil (Figure 2) and the charging cable, as well as the assembled and disassembled view.

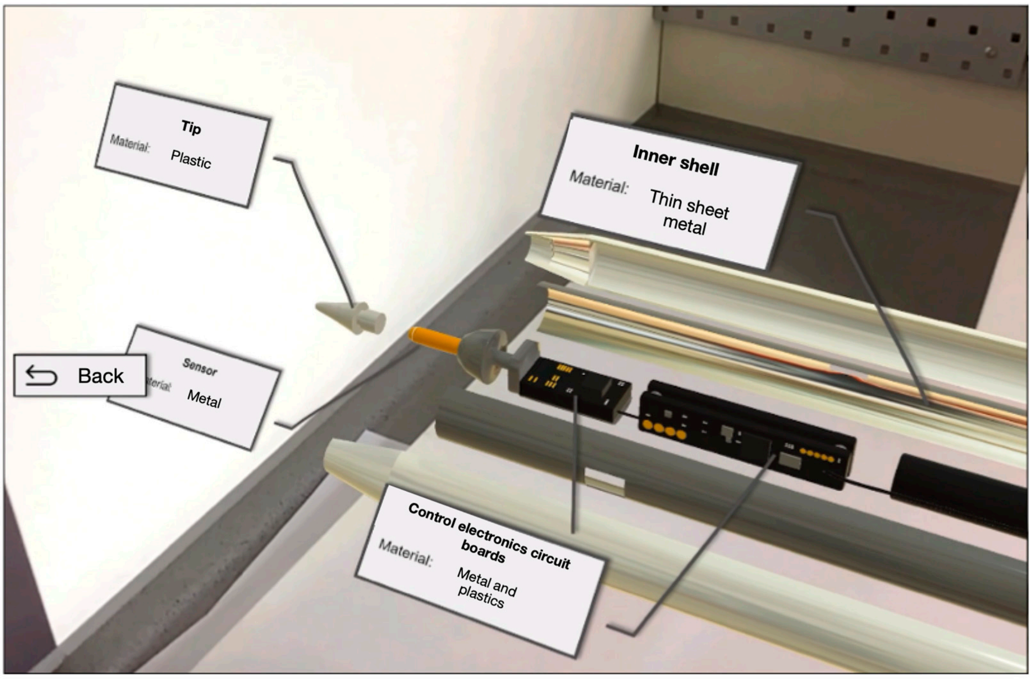

Figure 2. World tracking AR in disassembled view with text boxes for the name and material of the individual components of Apple Pencil.

Through world tracking AR, the students can view the individual components of the Appel Pencil or charging cable from all sides and physically approach or move away from the Appel Pencil/charging cable, zooming in or out. The text boxes in the blast view name the component and provide information about the materials contained there (Figure 2). Based on this, the learners should estimate how high the relative plastic content is in grams. The determination of the plastic content is intended to help students understand the relevance of plastics in the manufacture of technical end devices.

4.4. Sub-Topic 2: Properties of Plastics

In this sub-topic, students experimentally investigate the density and malleability of selected plastics or plastic products. The aim here is for the learners to explain the use or non-use of plastics in the iPad based on various material properties and to be able to explain the properties of the three types of plastics (elastomers, thermosets, and thermoplastics) at the particle level, made visible through an animated three-dimensional AR model.

In the first experiment, the students determine the density of polystyrene quantitatively and of polypropylene qualitatively. To do this, they place both samples in a beaker filled with water and add a measured amount of table salt until both plastic samples swim. The dissolved amount of table salt is then used to calculate the density of polystyrene. Here, the students discover that there are plastics that have both a lower and a higher density than water. Then, in the second experiment, the students test the deformability of three everyday products: rubber band (vulcanized rubber—elastomer), plastic film (PE—thermoplastic), and iPad circuit board (epoxy resin base—thermoset). Learners evaluate, based on their observations, the tensile strength and reversibility of the plastic samples. After the experiment, learners scan the Zapcode, which brings up an animated three-dimensional AR model of the three plastic types at the particle level (Figure 3).

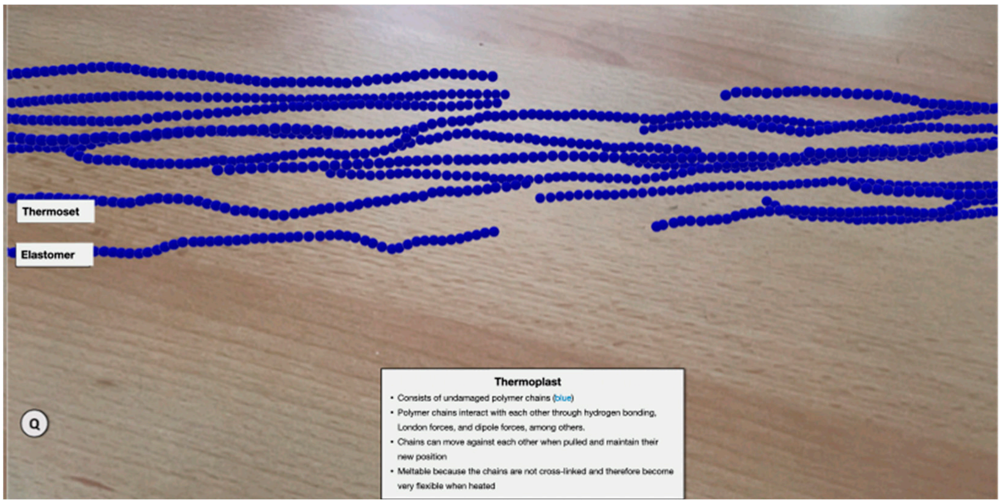

Figure 3. AR for modeling and explaining the structure–property relationships at the particle level for the deformability property using the example of a thermoplastic. End of animation: structure of a thermoplastic after the plastic has been pulled.

By tapping on one of the three plastic types, the corresponding 3D model appears, and a text box explaining the structure and the behavior is shown. At the button "An Kunststoff ziehen", an animation of the models runs, illustrating the behavior of the polymer chains when a tensile load is applied to the plastic sample at the particle level (Figure 3). The enrichment of the real experiment by visualizing the invisible through an animated three-dimensional AR model facilitates understanding the structure–function relationship of the plastic types. The experimental investigation of further properties was omitted for time and safety reasons. With the help of the contents of the AR and their preceding experimental observation, the learners should be able to name the respective plastic types of the examples used. In addition, they should explain how the selected plastic samples would behave when heated based on the molecular structure. To be able to introduce properties that are less easily or reliably determined experimentally and to compare the material properties of plastics, the densities, thermal conductivities, and melting temperatures or melting temperature ranges of various plastics and metals were given in a data table. Finally, the learners fill in a digital cloze via the LearningApps.org platform, where students fill in the blanks in a text with the correct words. Based on the experimentally collected data and the data table, reasons can be named for using or not using plastic components in the iPad.

4.5. Sub-Topic 3: Production and Processing of Plastics

In this sub-topic, the students deal with various aspects of the production and processing methods of plastics. For this purpose, three processing methods were selected that are frequently used and presumably applied in the production of iPad components. In addition to reactions or reaction mechanisms for manufacturing, the influence of additives on the properties of plastics, toxicological aspects of the reactants, and other aspects for evaluating criticality are addressed, such as demand, country risk, and country concentration. Learners obtain the related information by scanning the QR code. This brings up an interactive text designed with genial.ly. By clicking on one of the info buttons, learners receive elaborative information, definitions, videos, 3D animations, images, or diagrams. The law of figure-ground separation and the coherence principle were taken into account so that the interactively embedded content is better perceived by the learners and is relevant and appropriate to the respective text passage [27,30]. Using the text, learners assess country risk, concentration, and demand for plastics. Application or transfer questions relate the key points of the text to the iPad or its components, making the iPad the learning object. For example, learners should explain how a charging cable could be made from a thermoplastic rigid plastic using additives and name the processing method for the plastic coating. Finally, the learners explain the use of additives in the production of an iPad circuit board (based on an epoxy resin). The production of an epoxy resin or thermoset is shown with an animated three-dimensional AR model (image tracking), including explanations to dynamically demonstrate the viscosity change due to crosslinking of the polymers, which cannot be directly visualized through a static image or video (Figure 4).

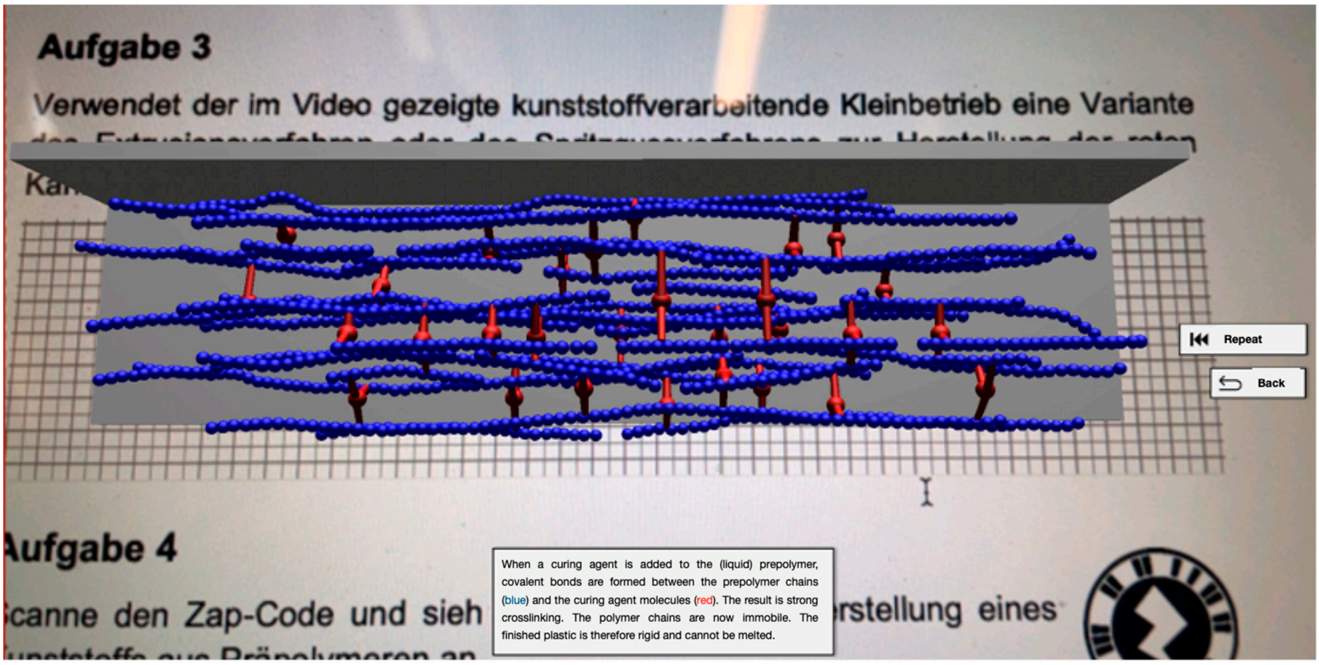

Figure 4. Image tracking AR. Animated representation and explanation of what happens at the particle level when a hardener (in red) is added to liquid polymers (in blue). The animation (addition of the hardener and effects on the structure) can be restarted by clicking the repeat button. The back button takes you to the structure of the polymer without a hardener.

4.6. Sub-Topic 4: Recycling of Plastics

The station focuses on recycling and separation processes for plastics and the associated problems. The station begins with a video on a German plastics company that operates in a circular economy, which can be accessed via a QR code. The video gives learners an insight into industrial processes and their benchmarks. In addition, the steps of (mechanical) plastics recycling are shown and explained in how “real” plastics recycling would work and which hurdles exist. In the corresponding tasks, these contents are to be reproduced and secured. The three recycling processes for plastics are taken up again in an information text explaining existing problems, including the cost factor or the need for clean separation of the different types of plastics. In the associated application and transfer tasks, the content is related to the iPad. For example, the learners assess the disposal and resulting recycling potential of the black thermoplastic iPad components or explain why an iPad contains relatively few recycled plastics [33]. Based on the information gathered so far, learners can take a position on whether exporting plastic waste is problematic and rate the recycling potential of plastics on a scale of 1 to 5. Finally, learners solve a logic problem to separate five (hypothetical) mixed plastics. The learners receive information on the density and solubility of the five plastics (PS, PA, PET, PMMA, PE) as well as access an interactive digital separation process designed with genial.ly (Figure 5).

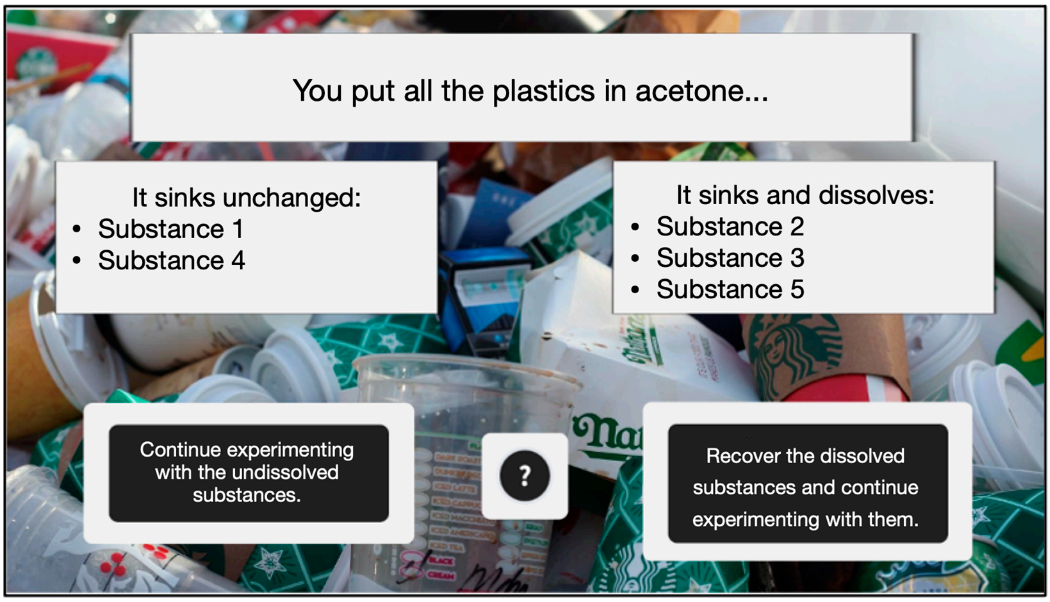

Figure 5. Excerpt from the interactive Genial.ly for the digital separation of the plastic samples. At this point, the learners receive the results for the solubility of the 5 samples in acetone. Now, they should decide whether they want to investigate the insoluble or the soluble samples further using the digital playbook. By clicking on the question mark, the learners receive help.

4.7. Sub-Topic 5: Substitution

This station focuses on alternatives to conventional, fossil-based plastics. The aim is for the students to be familiar with the term "bioplastic" after completing this station and to be able to question its occurrence in everyday life critically. In addition to naming alternative starting materials for plastics production, the learners should also become able to describe the synthesis of a polymer at the particle level, visualized through an animated three-dimensional AR model. To be able to evaluate biobased plastics as an alternative to fossil-based plastics, the learners have to deal with their advantages and disadvantages.

The task sheet's processing requires considering the interactive life cycle of a bioplastic designed with genial.ly, which is divided into four fields. The fields build on each other and must be processed in the order the cycle specifies. Content-related tasks accompany this on the learner's worksheet. By embedding interactive elements in the life cycle, it is possible to obtain additional information on each field in the form of (illustrated) info texts, images, an AR 3D model, videos, or synthesis instructions. This supports students' self-directed learning while reducing the cognitive load. Following the laws of figure-ground separation and closedness, the information elements are provided with a neutral, high-contrast background and a frame. Moreover, images that have a clear relation to the text are used [30]. Not only because of the possibility of combining different media systems but also because of the better clarity, the AR is accessed by scanning the Zapcode on the analog life cycle document (Figure 6).

The cycle title is already part of the first task since the inaccurate term bioplastic, often encountered in everyday life, is used here. Further, in the field of "Cultivation", possible plants for obtaining biomass are discussed.

PLA was chosen as an example of a biobased, biodegradable plastic because, on the one hand, it is one of the few commonly produced and widely applicable bioplastics [34]. On the other hand, the production takes little time (compared to, for example, plastics made from starch) and is feasible without unacceptable potential hazards [35]. In the field of "Production", the synthesis of a polymer is discussed using the example of polylactic acid (PLA). In an experiment, the students produce PLA themselves and should pay particular attention to the consistency or viscosity of the reactant and product. The viscosity change is to be explained using an animated three-dimensional AR model, which shows the dynamics of the particle level during the experiment or a step-growth polymerization (Figure 6). Symbols and processes shown in the model are named or explained using an associated info text. In the "Use" field, the advantages of biobased, biodegradable plastics are demonstrated by employing various possible uses and further highlighted by considering the problems of exclusively biobased and fossil plastics. An excerpt from a report on an Indian landfill is used to illustrate the environmental and health issues associated with landfilling plastics [36]. The advantages of biobased, biodegradable plastics, as shown in the previous fields, are leveled in the "degradation" field. The poor carbon footprint and the balancing act between the durability and degradability of a product made from PLA serve as arguments [37,38]. The use of entirely different materials and the elimination of plastics—using the example of the current packaging of an iPad [33]—are presented as "alternatives to the alternative". Because it cannot be assumed that the learners were familiar with packaging then and now, corresponding illustrations were added to the information box. This part of the station makes it possible to sensitize the students concerning the sustainable handling of "(plastic) waste" in accordance with the EU Waste Framework Directive [39].

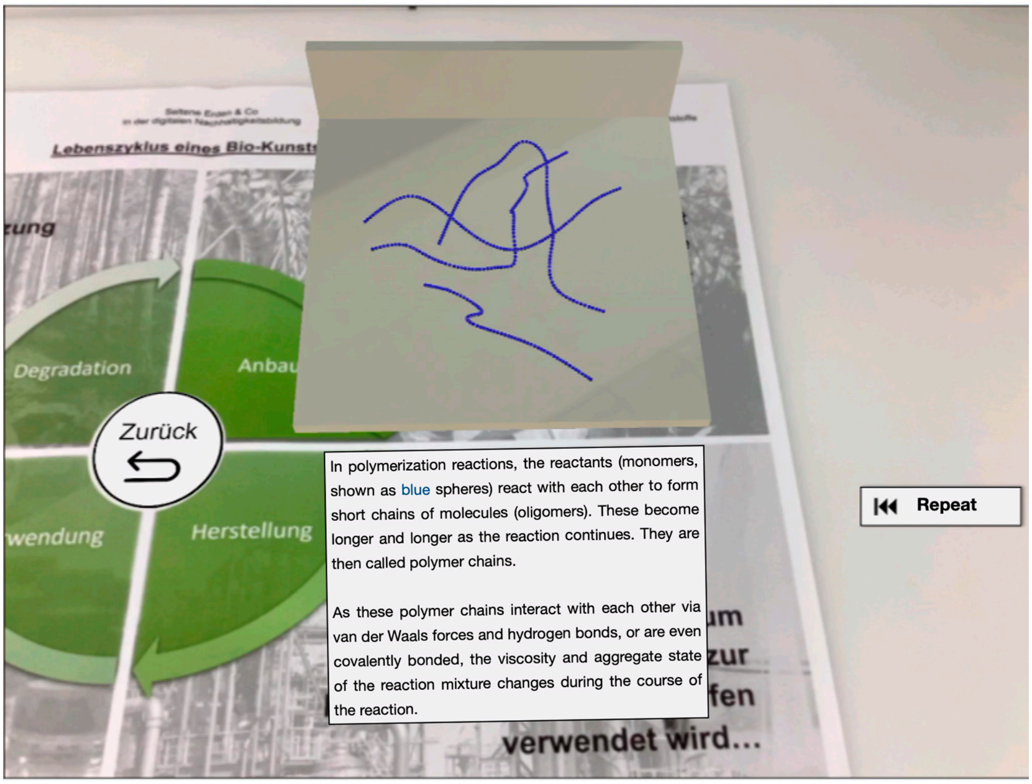

Figure 6. Section from the production of the augmented life cycle. An animated model explaining the polymerization reaction at the particle level is shown. End of the polymerization reaction: monomers have reacted with each other and formed a polymer chain. Animation can be restarted via the "Repeat" button.

4.8. Debriefing

Following the processing of the learning scenario, a debriefing takes place with the learners. In this phase, the focus is on process-related assessment competence and technical language communication. In addition to individual results from sub-topic 1, the evaluation scales of the groups for the areas of country risk, concentration, demand, substitution possibilities, and recycling potential are transferred to the online tool "Oncoo". Access to the tool is provided via a QR code. No registration or data protection critical transmission of personal data is necessary. If a criticality aspect shows widespread, individual deviations or even completely unexpected evaluations, a reason is requested, or the evaluations are discussed in plenary, and misunderstandings are clarified. In addition, the recycling potential and substitutability criteria are taken up in more detail by discussion questions such as "Does it make sense to replace fossil plastics with biobased plastics?" or "What is meant by a recycling-friendly product design?". Subsequently, a link back to the initial question of the learning scenario and the socio-critical problem presented at the beginning is to be established. For this purpose, the learners are given an augmented worksheet containing a spider's web diagram with six assessment categories for sustainability. With the help of their knowledge gained from the learning experience and the augmented information, the students are to assess the production quantity, the substitution potential of fossil plastics, the trade dependency, the risks for people and the environment in the production as well as in the disposal and recycling of plastics. Based on this, the students can reason on whether plastics should be used as materials for iPads (and more). This can be performed as part of a whole class discussion.

5. Results and Discussion

5.1. RQ1

The results indicate a high level of clarity regarding the design and provided information about the learning environment, as shown by the "I agree"/"I mostly agree" responses ranging from 87% to 88% across all sub-topics (Figure 7). All sub-topics also had specific questions related to clarity, and except for two, all received "mostly agree" responses with over 76% positive agreement.

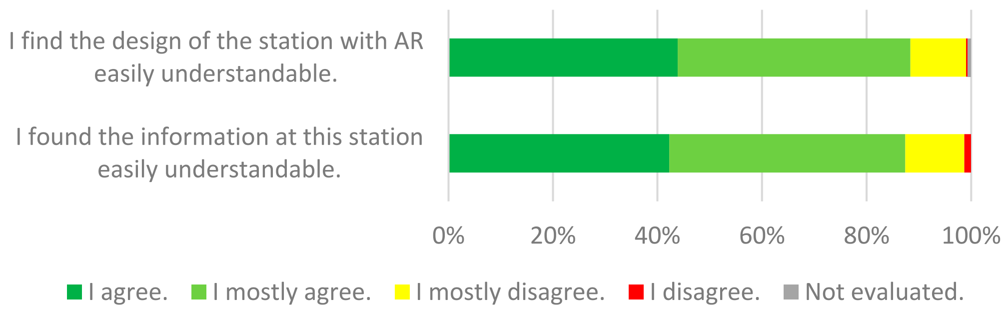

Figure 7. Understanding for all stations (recycling, production, properties, replacement, and structure).

The clarity of the definitions of country concentration and country risk received an 83% approval rate. The definitions that are used allow most learners to understand what is meant, and therefore, with minimal changes, they can be effectively used in this learning context. Overall, 76% of the participants stated "I agree"/"I mostly agree" that the AR models of different types of plastics helped them understand the properties of plastics better. The navigation through the digital life cycle of a bioplastic was rated as simple by 84% of the participants who agreed or mostly agreed. Both AR applications, thus, enhance perceived understanding, do not hinder the learning process, and promote self-directed access to information. Additionally, 83% of the participants found it easy to solve the gap text in the sub-topic about the properties of plastics. This can be interpreted as most participants feeling they understood the content and that the text is appropriately designed and enriched with AR. Simplification of the understanding of instructions through digital enrichment of a learning scenario (e.g., with AR) is also reported by Wozniak et al. [15]. A minority of up to 24% of the participants, on the other hand, experienced difficulties in solving this task. Therefore, further efforts need to be made to ensure their learning success.

In the recycling sub-topic, 80% of the participants would have liked the opportunity to check their solutions, which reflects research showing that direct and regular feedback positively impacts motivation and the self-guided learning process through self-checks [23,40]. The question regarding the sub-topic on composition received less than 30% agreement. This indicates that further elaboration is needed to assess whether this part helped in estimating the plastic content of the Apple Pencil and the charging cable and whether it should only be modified or if this assistance was entirely lacking from the participants' perspective.

5.2. RQ2

Sixty-four percent of the students disagreed or mostly disagreed that they prefer a 2D representation in the textbook over a 3D representation in the AR learning scenario (Figure 8).

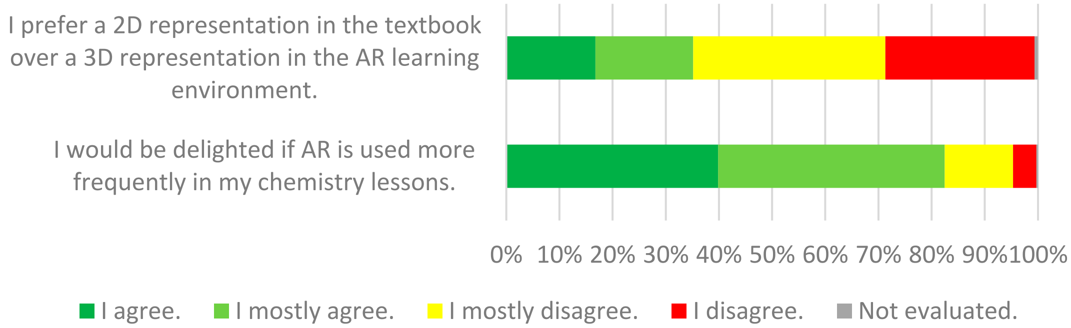

Figure 8. Use of AR for all stations (recycling, production, properties, replacement, and structure).

In addition to this, 82% of the students agreed or mostly agreed that they would be delighted if AR was used more frequently in their chemistry lessons. A positive attitude towards AR applications in class was also reported by Yu et al. [16], who found, among other things, that students evaluate AR in an experimental setting as helpful and (comparatively) effective. This indicates a strong desire to integrate 3D and AR elements more into chemistry lessons. However, these technologies must be applied not just for the sake of using the method itself but to serve the learning objectives effectively. For instance, educators can take these preferences into account when designing learning materials, ensuring that AR applications are thoughtfully integrated to enhance learning outcomes and engage students effectively. Simultaneously, the data show that not all students prefer 3D over 2D; therefore, spatial representation should only be used if it adds value. As shown by Sun et al. [14] and Wozniak et al. [15], in addition to the content of the AR environment, it is also important to consider the handling of the devices required for the usage of AR in order to ensure that the students are supported optimally in accordance with the Cognitive Load Theory [41]. Additionally, exploring the reasons behind the varying preferences for 2D and 3D representations could provide valuable insights into individual learning styles and preferences. At the same time, it should be noted that there are different AR applications for each station, and thus, a more specific research approach could provide more insights into their implementation.

Specifically, for the AR in the "Substitution" sub-topic, 86% of the students agreed or mostly agreed that the fixation on the surface was more practical than self-fixation. There also seems to be a preference for a fixed fixation that is related to the content or context. However, this aspect should be further investigated to gain a more comprehensive understanding of the preferences and implications of AR fixation.

The high approval rate of 90% regarding the statement that the instruction on how to use AR in the "Properties" sub-topic was helpful suggests that students value clear and well-structured guidance on using AR. The results imply that students benefit from such instructions and perceive them as valuable support to effectively utilize AR. Well-designed instruction instills confidence in students, enabling them to use AR successfully to enhance their learning. Therefore, the interpretation emphasizes the importance of offering such instructions in future AR-based lesson plans to promote student engagement, positive experiences, and overall learning outcomes, particularly when there is a justification for 3D registration.

In the "Production" sub-topic, 89% agreed or mostly agreed that the interactive info text was appealing. This can enhance engagement during the learning process [42,43].

Modern web technologies and mobile solutions offer better opportunities than ever before to create interactive experiences [44]. Influenced by their experiences with consumer websites and video games, today's learners also expect such interactive experiences in education. Interactivity not only makes the content more interesting but also facilitates more effective learning. Therefore, it is important to integrate media to unleash their full potential.

5.3. RQ3

In the context of situational interest, it is noteworthy that the negatively formulated item "I do not find it interesting" received a disagreement rate of 83% depending on the sub-topic (Figure 9). The appeal and interest in the design of the sub-topics were agreed upon by 84–86%.

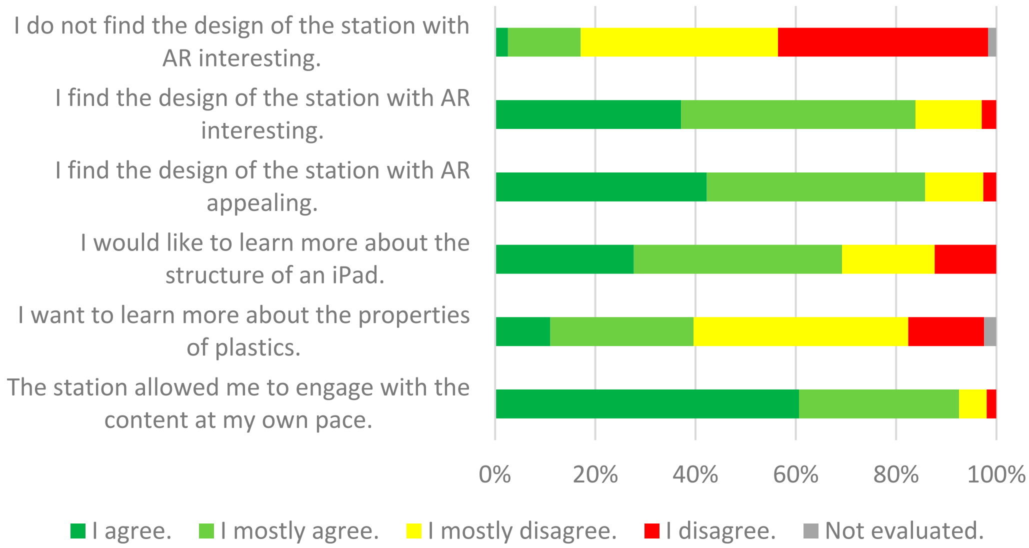

Figure 9. Interest in all stations (recycling, production, properties, replacement, and structure).

The data from RQ3 show that there is a higher demand for AR in the classroom, which supports these high levels of agreement. At the same time, it addresses the hold component of interest, as students would be pleased to see AR being used more frequently in their chemistry lessons. When specifically asked about the content of the station regarding plastics in iPads, more than two-thirds indicated that they have an interest in learning more about it. In general, there was mostly agreement (40% of students) to learn more about the properties of plastics. These results reflect the didactic debate that it is necessary to link learning objects to contexts to foster situational interest [45,46]. At the same time, the students indicated a high situational interest in the catch component, like other learning scenarios with a context [47]. As shown by Sun et al. [14], the utilization of AR can have a positive effect on the situational interest of students, which is in line with the results of the present study. The results also indicate that autonomy is positively associated with interest [48]. This highlights the importance of designing learning experiences and contexts to pique and sustain students' interest. Connecting learning content with relevant and engaging contexts can help increase students' interest, thus enhancing their motivation and learning performance. They reported that the sub-topics allowed them to engage with the content at their own pace (93%) [49]. At the same time, however, these results indicate that it is challenging to generate interest in the hold component and to engage students in the direction of their future actions. This would require a revision of the sub-topics.

6. Limitations

A consistent pattern emerged despite the varying time allocated to different groups for the tasks. It is worth noting that not all groups were supervised by the same teacher but by their respective teachers, which has advantages and disadvantages. While the generalizability of the results is a definite advantage, the comparability of the findings might be affected due to uncontrollable factors. To obtain more general results, testing the learning scenario in different schools, grades and with more students would also be helpful. Nonetheless, the overall outcomes provide valuable insights and trends, and by working with different teachers, we were able to mitigate the influence of biases and research enthusiasm.

The survey did not directly inquire qualitatively about the most interesting aspect of the level of perceived understanding; instead, the responses were based on the students preferences and the feedback provided for improvement. More explicit questions in the future could be beneficial to achieve a clearer triangulation of the data, but they were not the primary focus of this case study. While we cannot fully control all influences, we are aware of this limitation and have tailored our approach to our target user group, reporting on a field study conducted in the school setting.

The quantitative data collection process was not optimized. Since there is no association between the completed questionnaires and the individuals at each station, reliable data imputation is not possible.

The shortening of the Rheinberg et al. questionnaire means that we no longer collect the entire construct of current motivation from Rheinberg et al. [25]. However, we receive (time-efficient) feedback specific to our AR learning environment. Therefore, items also had to be specified, as the original items generally refer to "activity". We adapted this specifically to obtain explicit feedback on the AR environment. The students stated that they understood the questions, so we assume that validity can be accepted.

7. Conclusions

The findings of this study provide further evidence that providing an appropriate amount of information and integrating learning content with relevant and engaging contexts through appropriate choice of medium, e.g., AR, can enhance students' situational interest and motivation. The students expressed positive feedback regarding including critical aspects and the importance of learning autonomy and self-regulation, which they found beneficial. Additionally, they appreciated the clear instructions, appealing design, and meaningful integration of AR into the classroom, particularly in the context of plastics used in iPads.

Nevertheless, it is essential to acknowledge that there may be differing preferences and effects concerning the use of AR, which requires a more comprehensive investigation. Despite these findings, the study highlights the significance of tailoring educational approaches to meet individual student needs, incorporating engaging technologies, like AR, to create meaningful learning experiences and support students' interests, motivation, and effective learning outcomes.

Supplementary Materials: Supporting information can be downloaded at https://www.chemie.uni-konstanz.de/ag-huwer/forschung/downloads/augmented-reality/ (accessed on 1 April 2024).

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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 subjects involved in the study.

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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