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Comparing Augmented Reality in industry and Technology Education: Exploring teacher views and research needs

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Abstract
The use of Augmented Reality (AR) is a relatively new but significant trend in the educational landscape, including in technology education. The aim of this article is to discuss different perspectives on AR applications and describe the similarities, possibilities, and differences between them. Initial research in the field of technology education has shown numerous applications, especially since many tools, machines, and techniques must be learned in the hands-on practical sector, a discipline where AR is already being used in the industrial sector. However, there are even more applications in the industrial context. The resources utilized in these cases are often not available in the education sector, and the requirements for such systems differ between educational and industrial applications. When considering the specific application of AR in schools, it offers yet another perspective compared to educational research and industrial applications. Based on the results of an exploratory study among technology teachers in Lower Saxony, it becomes clear that costs, accessibility, and the lack (thus far) of appropriate learning materials are seen by teachers as the biggest challenges to effectively using AR in schools. It is noted that research and development projects in general technology education are necessary to effectively implement AR in technology education.

Keywords
Augmented Reality (AR), Technology Education, Educational Research

Introduction
In this article, the technical foundations of Augmented Reality, including a comparison with Virtual Reality (VR), are first discussed. This is followed by an examination of the use and research in this field from the perspective of industrial applications and education. The latter is presented both through the literature and a recent exploratory study among teachers in Lower Saxony. In a final discussion, these various perspectives are compared and analysed.

Augmented Reality
The terms VR and AR have become commonplace in everyday language, partly due to the gaming industry. However, the origins of these terms and technologies date back not to the 21st century, but to the late 1960s, with Sutherland's work in 1968 (Adelmann, 2020; Dörner et al., 2019). Various definitions of AR are found in the relevant literature, often referencing the definitions (or definition approaches) by Azuma (1997) and Milgram and Kishino (1994) (Mehler-Bicher, Steiger, 2022; Dörner et al., 2019; Adelmann, 2020; Hamann et al., 2020). While Milgram and Kishino categorize the term within the MR taxonomy (Milgram & Kishino, 1994; Milgram et al., 1994), Azuma stipulates conditions that must apply for AR (Azuma, 1997).

Figure 1 shows the Reality-Virtuality Continuum by Milgram and Kishino. The MR taxonomy indicates that the terms Augmented Reality, Virtual Reality, and Mixed Reality should not be considered synonyms; rather, there is a factual distinction between them. The specific overlay case that applies depends on the degree of virtual overlay. Thus, the continuum postulates a continuous transition between real and virtual environments (Mehler-Bicher, 2022). The continuum is bounded by two extremes. One extreme is reality, which describes the physical real objects and aspects captured by a medium or perceived in a real setting (Milgram & Kishino, 1994). The other extreme is virtuality, consisting solely of virtual objects (Milgram & Kishino, 1994). Between these extremes lies Mixed Reality, describing environments composed of both real and virtual elements. Depending on the degree of overlay or intensity of mixing of these environments, either Augmented Reality or Augmented Virtuality (AV) is present. MR describes both states, while AR is present only when the real component predominates within the environment. Thus, every AR environment is also MR, but not every MR is AR (Milgram & Kishino, 1994).

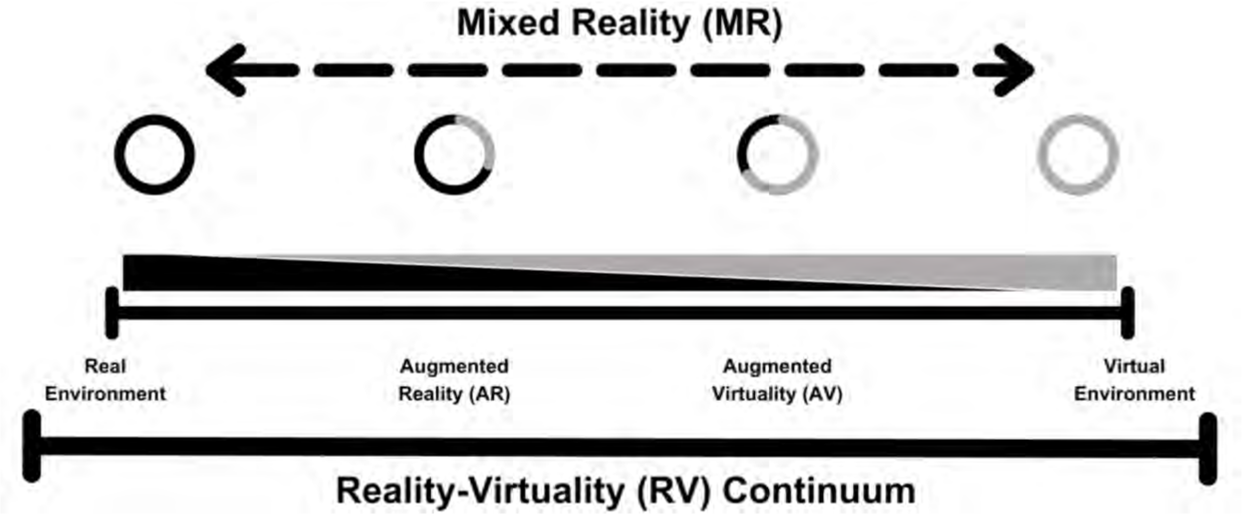

Figure 1. The Reality-Virtuality Coninuum own illustration based on Milgran et al. 1994, S.283

Azuma (1997) clarifies his AR postulate in his definition approach by identifying three main characteristics. Accordingly, an environment is identified as AR when there is a simultaneous existence of real and virtual environments with partial overlay, real-time interaction, and a three-dimensional relationship between virtual and real objects (Azuma, 1997). In popular science, AR is often merely limited to the enhancement of reality with virtual content. This limitation considers AR only in a broader sense; in a narrower sense, an environment can only be identified as AR if all of Azuma's main characteristics are present (Mehler-Bicher, 2022).

Wiemer and Rothe (2022, 2023) and Wiemer et al. (2024) discuss in the context of teaching-learning situations that there are two instructional dimensions for AR. On one hand, there is learning with AR, which activates learners through an AR environment to stimulate their own learning processes, and on the other, there is learning through AR, which explicitly involves learners in creating AR content. By doing so, learners not only build knowledge but also enhance their creativity and skills in AR technologies (Wiemer & Rothe, 2022, 2023; Wiemer et al., 2024).

It was already emphasized at the outset that the terms VR, AR, and MR are now present, although their origin dates back to the late 1960s. The appearance that these are new technologies can be attributed to the fact that these technologies have rapidly gained significance in industrial practice. This can be attributed to fundamental changes, such as massive advances in hardware for these technologies, matured ecosystems for developing solutions, and numerous synergies for VR, AR, IoT, and Machine Learning (ML), which mutually drive each other forward (Adelmann, 2020).

Applications of Augmented Reality in the Industrial Context

In the previous chapter, it was shown that AR is not a new invention but has gained increased relevance in industrial practice due to technological advancements (Adelmann, 2020). This development is characterized by improvements in hardware, software, and the integration with other technologies such as IoT and ML. Mobile technologies have significantly contributed to advancements in AR-relevant technology areas such as sensors, display technologies, wireless transmission, and battery performance. Microsoft's HoloLens is cited as an example of modern AR hardware, which, despite a limited field of view, is considered pioneering for the development of further improved head-mounted displays (Adelmann, 2020). Development environments like Unity3D, which simplify the creation of AR content, are also highlighted.

General Development

The significance of mobile AR, enabled by technologies like Apple's ARKit and Google's ARCore, is notable. These technologies have made AR accessible to a broad audience and laid the foundation for industrial applications (Adelmann, 2020). By utilizing existing development platforms and tools, AR applications can be developed efficiently and cost-effectively, promoting their use in the industry. Furthermore, synergies between AR and other technological developments such as VR, ML, and IoT/Industry 4.0 are discussed. These connections enable new use cases and foster innovations in their respective areas. The integration of Machine Learning, for example, enhances interaction with the real world in AR applications through robust recognition capabilities for speech, text, gestures, and objects (Adelmann, 2020). These points illustrate that the combination of technological advancements, integration with other technologies, and the development of more accessible tools increasingly make AR practical for industrial use. AR can enhance human-machine interaction and increase efficiency in production and maintenance, opening new perspectives for the industry (Adelmann, 2020).

Fields of Application

In the manufacturing industry, AR is used to enhance traditional production processes by integrating digital information into the user's field of view. AR can enable workers to see relevant data and graphical instructions over their real environment, which is particularly helpful in complex assembly tasks. This technology can help reduce errors, increase safety, and accelerate the training of new employees. AR can also facilitate the maintenance and monitoring of machines by visually presenting condition information and performance data (Dhanalakshmi et al., 2021).

AR can play a role in improving safety and efficiency in manufacturing processes. By displaying safety warnings and operating instructions directly in front of employees' eyes, accidents can be prevented, and work efficiency can be increased. AR technology can also be used to visualize complex components and assembly processes, which is particularly advantageous in the production of high-quality or critical components. AR enables interactive and dynamic adjustment of production processes in real-time, based on current operating conditions and requirements (Dhanalakshmi et al., 2021). In the context of Augmented Reality Aided Manufacturing (ARAM), AR is used to improve assembly accuracy and production efficiency. ARAM includes technologies that display work instructions and critical information about components and assembly steps directly in the workers' field of view, reducing the need to consult traditional construction plans or instructions. This directly embedded information helps minimize errors and ensure the quality of the final products (Dhanalakshmi et al., 2021).

The implementation of AR in manufacturing involves various technologies such as marker-based and markerless AR. Marker-based systems use visual markers to position information precisely, while markerless systems often use GPS and sensors to determine positioning. These capabilities can be used for a variety of applications, including for planning factory layouts, where digital planning data is transferred to real environments, allowing for more accurate planning and implementation. Moreover, this can be used to plan and simulate manufacturing processes, as well as to monitor production lines and perform safety checks. AR is also used for training and further education of employees by illustrating complex processes and providing interactive learning experiences (Dhanalakshmi et al., 2021). The combination of AR with VR offers additional opportunities, for instance, overlaying virtual prototypes with additional AR information. This can accelerate product development while simultaneously reducing the costs of physical prototypes. AR supports VR applications by providing contextual data that facilitate interaction with virtual environments and improve accuracy. This synergy allows for a more seamless integration of design, testing, and production, which is particularly beneficial in high-tech industries (Dhanalakshmi et al., 2021).

Potential

Sharma et al (2024) show that AR offers potential for automated driving. In a literature analysis, they show that AR can connect driving and road safety. Real-time data, intuitive route guidance and more advanced safety practices make driving more productive. At the same time, however, they also emphasise that there are risks and hurdles, such as information management and security, that need to be overcome (Sharma et al., 2024).

Rysbek et al. (2024), on the other hand, analyse an AR client with regard to its suitability for implementation in additive manufacturing. They implement an AR client in the manufacturing process of a 3D printer. The results show that the proposed client enables bidirectional communication between the 3D printer and AR client. The client makes it possible to see and operate the 3D printer software interface in a HoloLens2 (Rysbek et al., 2024).

Research and Development

AR is already being used in various ways in the industrial sector, although the mentioned application areas show that much research and experimentation is still ongoing, and some areas of application have not yet moved beyond the project stage. Research in the AR field focuses on further development of the technology, improving user experience, and opening up new application areas. A focus is on the development of more powerful and user-friendly AR glasses that offer longer battery life and better image quality. Additionally, researchers are working on improving interaction possibilities with AR applications through advanced gesture control and speech recognition. A summary of the usage potentials according to the Fraunhofer Institute for Design Technology Mechatronics (Fraunhofer IEM, 2024) describes the following application possibilities:

- Context-specific visual support for activities, e.g., in maintenance and servicing;
- Time savings, e.g., by eliminating the need for time-consuming information searches by technicians;
- Cost savings, e.g., by reducing training efforts and the elimination of paper-based documentation;
- Quality improvement, e.g., through visual inspection of work steps;
- Global availability of experts, e.g., through AR-based remote systems;

It is interesting to note in the overall view of AR application areas in the industrial context that many of the mentioned points can be prescribed in an extended learning area. Examples include information search, reduction of training efforts, and control of work. These are also points that could be relevant in the use of technology education. The same applies to the use of increasing safety or for simulating processes that would otherwise not be representable. Less relevant are areas like factory planning and the optimization of assembly efficiency, as these are less relevant in school education, which usually aims to gain initial experiences with technology.

Applications and Research in Augmented Reality within the Educational Context

As the previous chapter demonstrates, the fields of application for Augmented Reality (AR) in the industrial context are expanding, and correspondingly, AR is being increasingly researched. There are also various applications in the educational context, with a significant body of research in both the specific area of technology Education and in the educational context more broadly.

Academic Achievement through AR

In conceptualizing the learning outcomes of AR/VR applications, Schweiger et al. (2022) refer to two theoretical models that outline learning success from different perspectives, thus synthesizing the current state of research in the field of learning outcomes through AR. To capture learning outcomes from a technology context, they employ the SAMR Model by Puentedura (2010), while learning outcomes from an educational context are assessed using Schlicht's Structural Model (2014). The SAMR Model illustrates how digital technologies can be used to enhance learning methods. On the other hand, the Structural Model views learning as a multidimensional phenomenon consisting of five levels. While the levels of knowledge, skills, and abilities describe actions linked with cognition, sensorimotor skills, metacognition, and social processes, motivation describes emotions in relation to will or intent and the emotional process of action adjustment. The fifth level, attitude, represents a lasting object- and situation-specific value orientation concerning personal goals and motives (Schlicht, 2014).

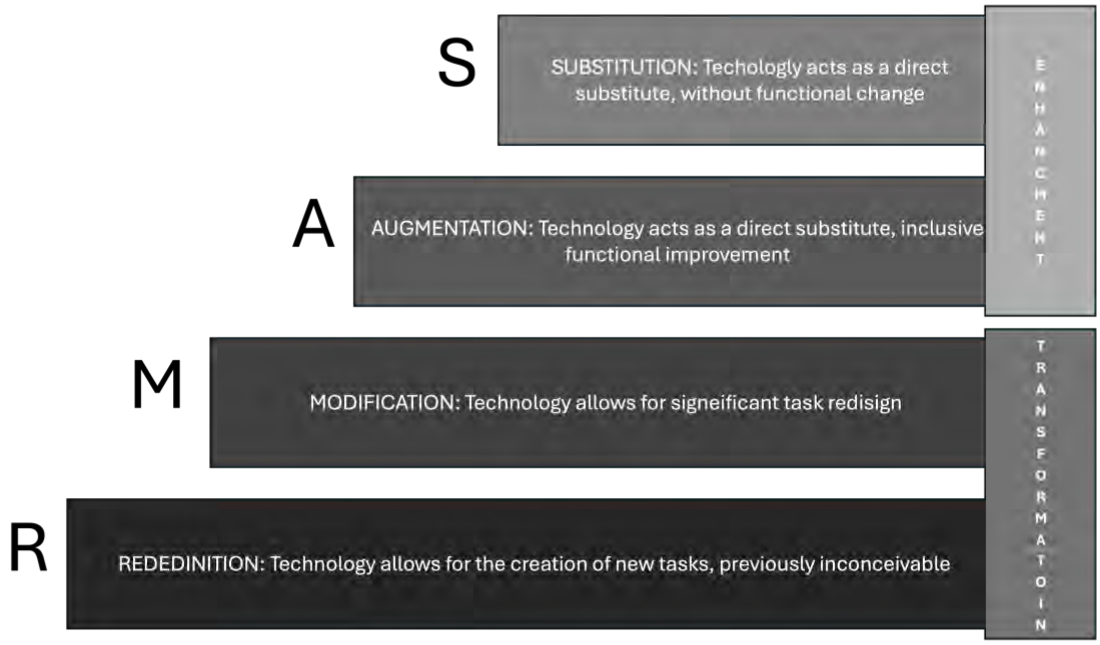

Figure 2. SAMR Model own illustration based on Puentedura (2010).

From the examination considering both the SAMR and Structural models, four contexts of learning success through AR/VR were identified. The first context is the technology context, which, according to the SAMR, can be divided into Substitution, Augmentation, Modification, or Redefinition. The media most commonly substituted by AR/VR are textbooks (n=20) and worksheets (n=13). Almost all studies (n=28) demonstrate that AR/VR introduces a functional extension of learning by visualizing and scaling abstract learning objects. Regarding Modification, it becomes clear that two important aspects of redesigning and enhancing learning processes can be observed. For example, the combination of AR/VR applications with existing media output devices holds potential for creating immersive learning environments with digital and game-based learning concepts. Another aspect is that learners, through the implementation of immersive learning environments, can themselves determine the pace and duration of learning. Immersive learning environments also create new learning opportunities (n=8). Learners can use AR/VR technologies to learn asynchronously, explore virtual learning spaces individually (n=21), or learn at home using the Flipped Classroom model (n=13) (Schweiger et al., 2022).

Regarding the Structural Model, learning success in the educational context was also noted. For instance, procedural knowledge about methods and techniques or problem-solving strategies is enhanced in school settings through immersive learning environments (n=27). Declarative knowledge about terms, conditions, and events is also supported (n=23). In terms of skills, AR/VR technologies can enhance the perception of multisensory abilities through novel visual, auditory, and sometimes tactile stimuli (n=18). Learners' own stock of knowledge (n=20) through reflection on what is learned after using immersive learning environments and collaborative learning through AR technologies (synchronous n=16, asynchronous/online n=20) can be fostered. The mere use of immersive learning environments is already seen as a motivational factor (n=11). The acceptance of technology and learners' attitudes towards AR/VR technologies as learning objects are consistently viewed positively (n=25). In terms of media literacy, Schweiger et al. observe that the primary focus of investigations in the school context is mostly on reception and impact, rather than on learners' own creation of AR/VR applications (n=25) (Schweiger et al., 2022).

Other contexts of learning success include temporal and psychological contexts. Scientific studies predominantly indicate short-term effects since the investigations are gathered through observations or interviews immediately after the use. Research by Southgate (2019) concerning VR usage shows that learners can remember the learned content better in the long term.

Similarly, Wiemer et al (2024) show that the long-term use of AR technologies must first establish itself in daily use before long-term success can be attested. Psychologically, it is noteworthy that predominantly cognitive effects are identified (n=29). However, this can also be explained by the fact that the search criterion of the review study was learning success (Schweiger et al. 2022). The results of the study show that AR/VR technologies are already being investigated in the school context, with it being clear that, in particular, learning with AR as classified by Wiemer and Rothe (2022, 2023) and Wiemer et al (2024) is being investigated. This is not surprising considering that the technologies must first be examined regarding their suitability before it can be considered how students can create their own environments. Thus, it is shown that handling the technologies promotes acceptance of the technology. With growing acceptance and media competence in handling the technology, it is easier for learners to also consider the other side of the technology and thus focus on learning through AR.

Selected Examples

An example of learning through AR being applied is shown by Rigling et al. (2024). Within the framework of the project digit@L, students developed their own AR/VR environments, which are supposed to contribute to students building knowledge and skills for creating technology-based experiential worlds (Rigling et al., 2024). As an example, the authors cite an AR application designed by students. The AR application was developed by students of technology pedagogy. The content focus was on the disassembly of a gearbox. Thus, the students created an AR-based disassembly plan for a gearbox by creating the CAD files of the gearbox themselves and integrating them into the AR application Jigspace. A detailed disassembly plan was developed in six steps, which should contribute to learners' reasoned creation of a disassembly plan for the gearbox (Rigling et al., 2024). Rigling et al. (2024) show, albeit exploratively, that by creating immersive learning environments, students develop situational interest in technology-based experiential worlds (Rigling et al. 2024). The learning process of technology acceptance regarding immersive applications is thus stimulated both by learning with and by learning through AR.

Overall, Rigling et al. (2024) state that students acquire the handling and acceptance of the technology through the creation. We would like to go further at this point and make assumptions that are not mentioned in Rigling et al. (2024). Looking at this scenario, this simple AR application can be considered in several ways. For example, the students develop an environment for learners. The learners who use the AR application for disassembly are therefore in the "learning with AR" aspect. The learning success and the competences that can be acquired through this have already been shown in Schweiger et al (2022). As Rigling et al. (2024) exploratively describe the students who have built the AR environment develop competences in the area of dealing with and accepting the technology. Accordingly, they are in the aspect of learning through AR. At this point, we would like to add another aspect and make the assumption that the students have also developed competences and expertise with regard to the content itself by creating the digital disassembly. The creation of an AR environment can of course also be understood as a teaching-learning strategy, similar to creating your own tutorials (Wolf, 2015; Ebner & Schön, 2017). In this way, the concept of learners developing their own tutorials promotes a deeper penetration of the content to be explained, as it is necessary to understand how the principle to be explained works (Wolf, 2015). We see it similarly when creating an AR environment that is intended to stimulate learning. We assume at this point, even if it certainly still needs to be investigated, that the students who created the disassembly plan have penetrated the gearbox in its overall complexity before they were able to prepare the AR content accordingly. Learning through AR would also work in this way.

Furthermore, AR allows practical experience with technologies and equipment that would otherwise be inaccessible for cost reasons or due to safety concerns. Through the simulation of real applications, students can gain valuable practical experience without the real risks. Regarding professional competence, Heindl and Pittich (2024) cite the virtual welding training room by Weldplus as an example. There, trainees use equipment (AR headset, controller) modeled after real welding equipment (visor, burner) (Heindl & Pittich, 2024). The AR simulation prepares for working with real welding devices, thus minimizing the risk potential (Prange, 2021).

Additional Perspectives

In addition to specific industrial applications, AR also offers significant opportunities for general technical education. Müller and Kruse, for example, show that 73.5% of all AR technologies are used in the educational context in higher education, although strictly speaking this remains at the level of learning with AR (Müller & Kruse, 2022). Furthermore, they show that the area of application of AR in the teaching/learning context is dominated by the natural sciences at 49.2% (Müller & Kruse, 2022). One example is the use of AR for the plastics industry and microplastics (Krug et al., 2022). AR technology is used to make the material properties tangible and to encourage collaborative work (Müller & Kruse, 2022). By using AR, teachers can convey complex concepts and processes in a vivid and interactive way. For example, students can view and manipulate virtual machines or systems in the real environment of the classroom, which promotes a deeper understanding of and interest in technical disciplines. The most common topics emphasised by Müller and Kruse in their systematic review are electrical engineering and technical drawing (Müller & Kruse, 2022). This seems logical in principle, as the complex world of electrical engineering in particular can stimulate other approaches through an AR application. Wiemer and Rothe (2022) showed in a study of the support needs of technology students that electrical engineering is one of the fields with the greatest need for support. Müller and Kruse also show that 61.8% of the studies identified use AR within a didactic framework in the teaching/learning context. Of these, 23.5% are virtual aids. A clear prioritisation of mobile (47.1%) or stationary (52.9%) AR solutions could not be determined (54). In 47.1% of the studies, the focus of the AR application is on the successful transfer of knowledge, while 32.4% aim to improve spatial awareness. In contrast, 14.7% investigated the change in work performance through the use of AR technologies (Müller & Kruse, 2022).

In summary, it can be said that the topic of AR technology education, as well as in education more broadly, is indispensable. Furthermore, there is a high level of research interest in learning outcomes, which seems logical in the educational context. The fact that much research is still conducted with students is also a sign that there is still a significant need for research and development, as these studies in the educational context usually take place before research is conducted in schools.

The Perspectives of General Technology Education Teachers on the Use of Augmented Reality in the Classroom

The Technology Education Working Group at the University of Oldenburg annually hosts a professional development day for teachers from Lower Saxony in the field of General Technology Education. Here, they can attend various workshops to further their professional skills. In 2023, the theme of the professional development day was future technologies, offering trainings in Maker Education, Robotics, and Augmented Reality. About 40 teachers participated in total.

As part of the augmented reality workshop, a system already in use at the university was first presented. The technical principles, conditions of use and possible applications of AR in the field of general technical education were then discussed. The teachers were also familiarised with the basics of the programme using an exact example. This served to demystify AR technology and familiarise the teachers with the low-threshold nature of the programme. There was also a forum in which further possible applications and difficulties with implementation were discussed. This served to encourage teachers to actively think about implementing AR in their school context. Eighteen teachers took part in this workshop as part of the training day**.** Following the workshop, the participating teachers were asked whether they already use augmented reality in their lessons and in what form. The survey also asked about the obstacles and problems that currently hinder its use. The aim of the survey was to generate initial indicators for future research and development perspectives, so it was an exploratory study (Stein, 2014).

Methodological Framework

A semi-open questionnaire was chosen as the methodological tool for the survey. The use of such a questionnaire is methodologically advantageous for several reasons. First, the semi-open questionnaire allows for flexible data collection, providing both standardized, comparable data through closed questions and deeper insights into personal attitudes and experiences through open questions. Second, the semi-open approach supports hypothesis development in exploring a new field, which can later be tested with quantitative methods. Finally, this questionnaire approach allows for high adaptability and responsiveness to the respondents' answers, especially when the research field is still so open and new (Bortz & Döring , 2002).

The questionnaire consisted of four questions, two of which focused on actual usage and therefore used a closed response format. Additionally, the questionnaire included a semi-open question on the reasons for not using AR and an open question on the challenges of using AR. All the teachers who participated in the workshop also took part in the survey, so n=18, although one teacher did not provide an answer to one question. The analysis was carried out using descriptive statistics to provide a summary and clear presentation due to the exploratory research design (generating initial indicators for research perspectives) (Bortz & Döring, 2002), and simple content analysis methods were used for the open questions to interpretively discern meaning structures in the answers (Reinders et al. 2015).

Results

The data analysis (Figure 3) revealed that, to date, only two of the 18 surveyed teachers have implemented Augmented Reality in their teaching. Accordingly, only these two could specify how they use AR. Here, they could choose between "theoretical", "practical", or both in a closed response format.

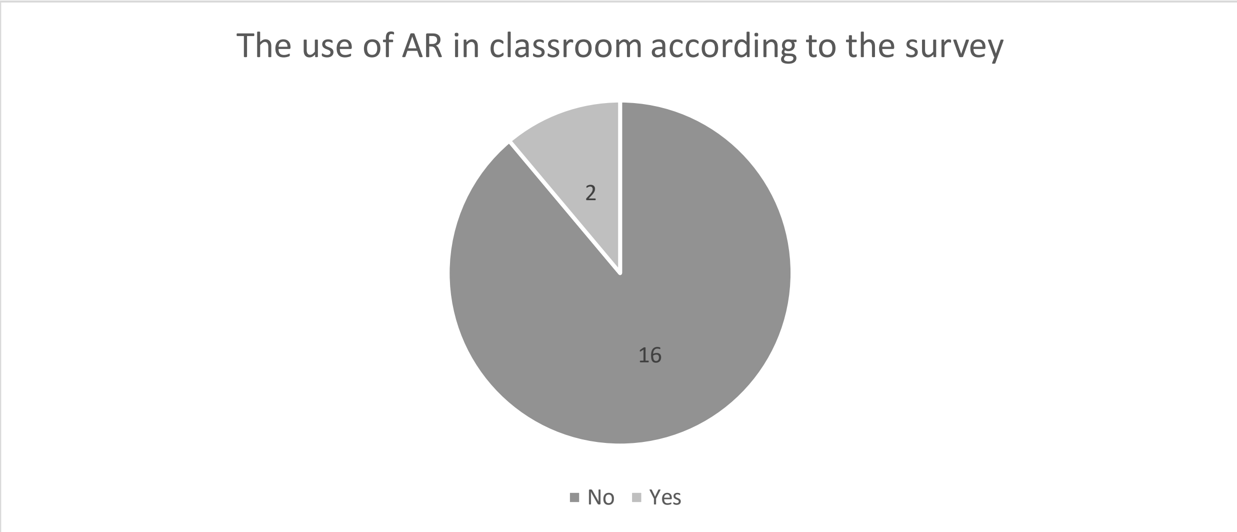

Figure 3. The use of AR in classroom according to the survey (n=18).

In another question with a closed response format and the option to add personal points, the teachers were asked why they currently do not use AR in their teaching. This question also allowed for multiple answers, as it was assumed that several reasons might simultaneously play a role. The n for this question was 17, as one teacher did not provide an answer.

The results (Figure 4) show that the curriculum and the facilities are least cited as reasons for not using AR, with only one or two mentions each. Lack of familiarity with the topic and no time for training were each mentioned five times, while the absence of appropriate teaching materials was mentioned six times. The most common reason given was "Too expensive to acquire and maintain," cited by eight of the 18 surveyed teachers. One teacher, who mentioned their own reasons, described the subject as too complicated for their target group and indicated they work in special education.

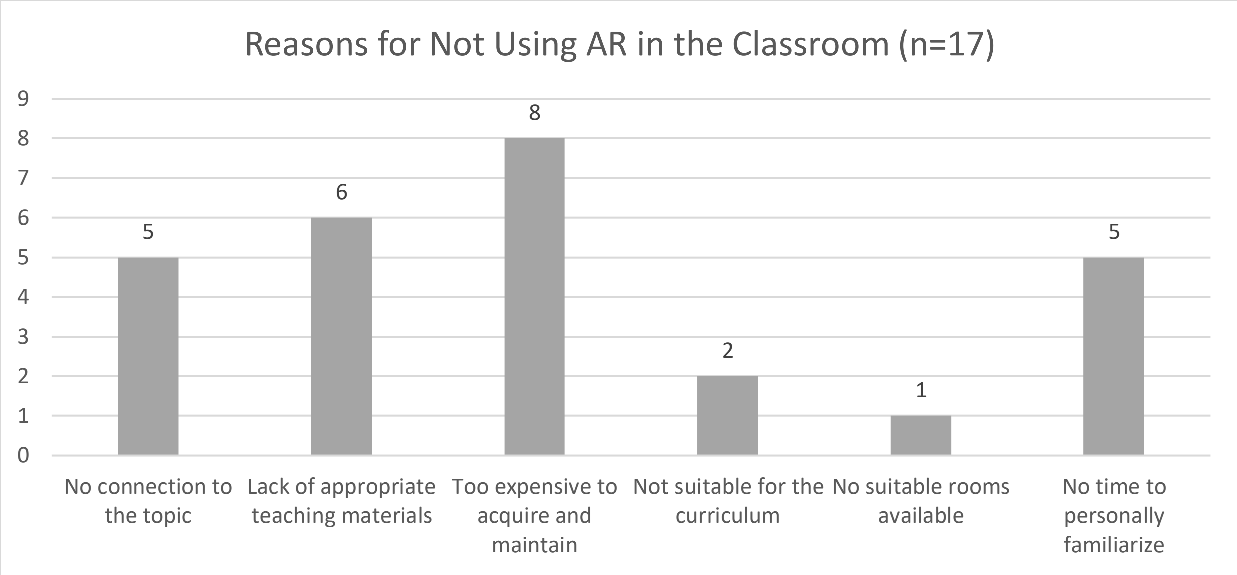

Figure 4. Reasons for Not Using AR in the Classroom (n=17).

The final question of the questionnaire related to challenges posed by Augmented Reality in technology education and was posed in an open format. The aim of this question was to gain a broad overview of the topic from the teachers' perspectives. The points mentioned could be categorized into several main categories: costs and resources, technology and subject-specific competencies, software and its handling, and didactic considerations:

1. Costs and Resources: Several comments referred to the financial and time expenditures associated with the introduction and use of AR in the classroom. It is clear that the costs for software and the necessary hardware (tablets, smartphones) are seen as significant barriers. Additionally, the cost-benefit ratio is questioned.
2. Technology and Subject-Specific Competencies: Basic knowledge is deemed necessary, and there are concerns about the complexity of the programs and the ability of the teaching staff to familiarize themselves with the new technology.
3. Software and Handling: Comments highlight that the existing software is perceived as too expensive, complex, and cumbersome to learn. The need for educational licenses and intuitive usability is emphasized, pointing to the importance of user-friendliness for successful integration into everyday school life.
4. Didactic Considerations: Some remarks reflect the concern that AR might be used for its own sake, without making a meaningful contribution to the learning process. The necessity to create meaningful and timely applications that are tailored to the age and abilities of the students is stressed.

The recurring themes of costs and handling complexity suggest that the teachers perceive a gap between the available AR technology and the practical realities of the school environment. Overall, the data reflect a picture of skepticism among teachers, coupled with a desire for more accessible and user-friendly solutions to implement AR meaningfully in the classroom. The latter indicates that the skepticism is fueled by perceived lack of solutions from the teachers' perspective, not as a fundamental rejection of new technology. In addition, it is crucial to establish long-term support structures for teachers to ensure they are able to continuously develop their skills in using AR technologies. Ongoing professional development and collaboration between schools and technology providers could help bridge the current gap between the availability of AR tools and their practical application in the classroom.

Discussion

The study reveals significant hurdles in the implementation of AR in the educational sector. The surveyed teachers see costs and technical complexity as particular challenges. Future research and (educational) development projects in the use of AR in technology Education could focus on developing cost-effective and user-friendly AR applications specifically designed for educational purposes and pedagogically linked with appropriate teaching materials. Another field of research emerges in the development and evaluation of learning settings that integrate AR, as well as in the area of teacher training for the necessary technology competencies. Another important research area could be the didactic potentials of this technology.

Conclusion

The use of Augmented Reality (AR) has made significant progress in both industry and education, showing great potential. In industrial applications, AR enables the efficient execution of complex tasks by allowing users to integrate information directly into their field of view, increasing productivity and reducing errors. These advances have been driven by improvements in hardware and the integration of key technologies such as IoT and machine learning.

However, in the educational sector, particularly in technology education, several obstacles still hinder the widespread implementation of AR. These challenges include cost, accessibility to necessary technologies, and a lack of adapted teaching materials. As a result, it is difficult for educational institutions to fully utilize AR as a teaching tool. Although teachers recognize AR's potential to enhance engagement and improve the learning experience, they often lack the resources and technical expertise for effective integration into the curriculum. To ensure the long-term integration of AR in technology education, continuous support and training programs for teachers are essential. These programs would help overcome technical and financial barriers while fostering the gradual adoption and effective use of AR in daily teaching practices.

For this reason, targeted research in technology didactics is crucial. Future projects should focus on developing affordable, intuitive AR applications specifically designed for educational purposes. Equally important is the creation of teaching materials tailored to AR technologies. Furthermore, AR offers opportunities for more individualized learning experiences, allowing students to explore complex technical concepts at their own pace. This is particularly beneficial in technology education, where hands-on learning is key. Research in this area could also aim to develop empirically based methods to introduce teachers to the technology and expand their pedagogical skills. Moreover, collaboration with the education sector offers valuable insights for the AR industry by exposing it to the specific challenges of classroom implementation. This feedback loop can lead to the development of more adaptable and user-friendly AR solutions that benefit both education and other sectors.

Finally, partnerships between the education sector and the AR industry could accelerate the development of tailored, accessible AR tools. Such collaborations would also give schools access to advanced technologies and professional expertise, fostering innovation. These initiatives could bridge the gap between the current use of AR in schools and its enormous educational potential.

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