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The Benefits and Challenges of Augmented Reality in the Science Classroom: A Narrative Review

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Abstract

The use of augmented reality (AR) to facilitate learning in the science classroom is an understudied topic that has only recently begun to be explored. A number of studies performed by academic researchers in science classrooms have indicated that these technologies have much to offer toward improving learning outcomes although challenges still present, but it is teachers' experts in the field who will be called upon to deliver this instruction, making an understanding of their perspectives regarding these technologies critical. In this narrative review, recent literature is synthesized to understand what teachers and other education experts note as the benefits and challenges of using AR in the science classroom, as well as the most effective ways to address those challenges. The review concludes that both the benefits and challenges identified in such studies appear commonly across countries, grade levels, and natural science subjects, indicating that the identified approaches to addressing these challenges might have wide-ranging appeal and positive outcomes for the future.

Keywords: Augmented Reality (AR), Technologies, Science Classrooms, Benefits, Challenges, Narrative

1. Introduction

Augmented reality (AR) has expanded rapidly in use in classrooms all over the world with the invention of new technologies and a growing availability of applications. In primary science classrooms, students can use AR applications as supplementary resources to further traditional instruction in general science (Salmi et al., 2017), biology (Güntepe & Usta, 2021), geology (Nielson et al., 2016), and even physics (Volioti et al., 2022). Nursing students in university classes can examine the respiratory system via an image superimposed on a tablet screen that is interactive and allows for exploration (Nielson et al., 2016, p. 160). Students in a range of medical science classrooms can use projected images to simulate surgical procedures, visualize cellular structure, and observe biological functions (Barrow et al., 2019, p. 3). The potential for AR to revolutionize classrooms is wide-ranging, but an understanding of its benefits and challenges, as well as how to best address those challenges, has sparked all new questions as to how these technologies can best be applied in diverse disciplines, such as science education. Studies on the use of AR technologies in classrooms have, as a result of the expanded use of such technologies, been prevalent only in recent years. Academia wrestles with all new questions around how AR can be used in classrooms with digital natives despite the relatively newness of its applications. These are questions that require timely and comprehensive answers, particularly since students are so often faced with such technologies in their

lives and studies with students using AR technologies have been shown to help students better understand abstract concepts and visualize scientific processes, increase their motivation to learn, expand access that makes science learning more inclusive, increase the level of engagement for students, and, as a result, significantly improve learning outcomes. However, the challenges faced by teachers and education technology experts are also significant and will require them and the schools in which they serve to invest time and resources to overcome. The response will need to be three-fold: schools must be supported in improving infrastructure and access to technologies, teachers must be supported in learning about technologies and how to best use them in the classroom to achieve learning goals and meet standards, and students must be supported by providing the best resources to improve learning outcomes and prepare them for the future. As the use of these technologies continues to grow in the years to come, such investments will be crucial for a motivated and knowledgeable workforce.

1.1. Background

The use of AR technologies of all kinds has expanded rapidly in recent years, demanding that teachers become knowledgeable about the effective use of such technologies (Yilmaz, 2021, p. 136). Augmented reality technologies, a group of applications and devices which offer an interactive experience that "combines real and virtual objects in a real environment, runs interactively and in real time, and aligns real and virtual objects with each other," (Azuma, et al., 2001, p. 34), allowing virtual objects to be projected onto a real space, are a useful supplemental tool for instruction in the science classroom. In these classrooms, "the separate environments of the real world and the virtual world form a reality" which brings into visual reality a host of scientific processes and phenomenon for students (Salmi et al., 2016, p. 254). AR technologies include image projection, quick response (QR) codes, interactive video games, and a host of other applications and delivery methods.

As an educational medium, AR is used in classrooms via smartphones, headsets, tablets, and internet applications which enhance lessons and allow students to better visualize concepts. Applications range from hands-free technologies to more highly interactive ones, providing a range of different affordances for learning (Radu & Schneider, 2019, p. 544). For science learning, AR is particularly suitable for learning abstract concepts and complex processes. While studies on the use of virtual reality in education have surged since the early 1990s, the use of augmented reality (AR) and its benefits and challenges in the classroom has become more prevalent as a topic of research only more recently, in approximately the past ten to twelve years (Barrow et al., 2019). Despite conclusions reached by these studies indicating that AR technologies are potentially highly beneficial to students in science classrooms, the use of these technologies is still exceedingly limited in the modern science classroom (Fearne & Hook, 2023, p. 330). The challenges of using AR in science classrooms, which can prove costly and time-consuming to address, are a common barrier to the expanded use of these applications.

1.2. Related Studies

In science classrooms around the world, studies indicate that the use of AR technologies is both beneficial and challenging for students. As researchers explore the use of different applications and software that allow AR technologies to bring science lessons to life, the data they collect regarding these benefits and challenges is illuminating, with common themes related to the benefits and challenges identified by researchers in using these technologies in science classrooms and drawing conclusions about the outcomes of such use. The themes that emerge show that preparing students for the future, allowing them to visualize science concepts and processes in new and innovative ways in the classroom, and increasing student engagement and motivation to learn improves learning outcomes. However, in studies with students using AR in the classroom, some challenges also present; notably, infrastructure issues, the quality of some available AR resources, and the amount of time it takes to set up and learn new applications and technologies are common concerns.

Academic research notes the importance of preparing students in science classrooms for a future in which internet technologies like AR will be prevalent in classrooms in the future and in the workplace (Barrow et al., 2019, p. 1). The impact of internet technology on classrooms around the world is both "inevitable and significant" according to researchers studying its rapidly expanding use (AlNajdi, 2022, p. 9). Students born after the turn of the 21st century, the "digital natives" populating classrooms all over the world, come to class immersed in the world of

computers, the internet, and digital technologies, making traditional teaching methods less engaging and requiring the use of technology in the classroom to keep learners motivated and prepared for life outside the classroom (Al-Anazi & Khalal, 2022, p. 1064). Yilmaz (2021) notes that internet technologies like AR are prevalent in the daily lives of everyone in the digital age and are emerging tools for use in the classroom with the potential to improve educational outcomes (p. 136). AR technologies, when applied to science teaching and learning, allows participants to "gaze into the future" and feel as though they are a part of the future of learning (Barrow et al., 2019, p. 6). In fact, Radu & Schneider (2019) refer to these technologies as "emerging" with "the potential to radically transform science education" (p. 544). With a transformed method of instruction comes new methods of preparing teachers for the classroom, and science education is ripe for new paradigms.

One of the most important benefits of the use of AR technologies in the science classroom is the ability to "make the invisible observable," or allowing for the visualization of science processes and concepts (Salmi et al., 2016, p. 253). In the study performed by Yilmaz (2021), the researcher noted student responses to questions about the benefits of AR technologies in the science classroom mentioning AR's ability to make science processes more visible, saying that the allowance of observation of science processes and phenomenon made AR technologies useful in the classroom, allowing for greater participation through observation and investigation (p. 142). In a study of university students engaging with geological concepts using 3D sand tables, students were determined to have an increased geospatial understanding of the concepts when compared with students who had learned the same concepts without the use of AR technologies as a supplemental resource (Moore, et al., 2020, p. 244). In a study of high school physics students, Arymbekov et al. (2023) found that the increased ability to visualize concepts using AR technologies made the advanced lessons taught in class more "tangible" for students, resulting in higher post-test scores and increased confidence in grasping complex subject matter reported by students (p. 60). Visualization is a benefit that AR has a unique ability to offer to science students, a field of study in which such visualization is particularly critical for observation and investigation to increase comprehension.

Another benefit of using AR technologies in science classrooms is a reported increase among students in their motivation to learn. For students to "engage in cognitive functioning," pressure must be exerted or motivation to learn must be present, and research has shown that AR technologies, used effectively in the science classroom, have the potential to motivate students to learn (Al-Anazi & Khalal, 2022, p. 1064). The use of QR codes in the classroom to engage with lessons led students to report feeling both motivated and enthusiastic to learn further about the subjects they studied and the material with which they interacted, leading them to seek more information on topics introduced in the science classroom after leaving class (AlNajdi, 2022, p. 10). Salmi et al. (2016) notes that improved results related to increased situation motivation in the science classroom were somewhat divided by gender, with boys benefitting more from the motivational aspect of the use of AR technologies in science lessons than girls, indicating that boys who feel motivated to learn in the science classroom, feeling inspired by such technologies to explore further and become more interested in science learning, had much to gain from the use of these technologies in science teaching and learning (Salmi et al., 2016, p. 264). The lower the motivation reported, the lower students scored on the post-study knowledge tests; however, those students with the lowest pre-test knowledge benefitted more from AR technologies in the science classrooms, indicating that prior knowledge plays a critical role in student motivation to learn (Salmi, et al., 2016). Using these technologies to increase the motivation to learn can, for many students, spark interest in new subjects and feel inspired to learn more about them, bringing more and more prior knowledge to each subsequent lesson.

AR technologies, when used effectively in science classrooms, also aids in increasing comprehension levels. Yilmaz (2021) reported "significant" differences in student comprehension following the use of AR technologies in science classrooms, observing that AR application allows for a "new perspective" on laboratory experiments, which are historically of significant value in science education (p. 143). Maulana et al. (2020) had similar findings in a study of seventh-grade students using mobile-based AR media in the classroom to learn about biology and human system functions, noting that increased motivation levels resulted in increased learning outcomes and increased comprehension of new topics for students who engaged with these technologies during the lesson (p. 364). The practical application of science learning through the use of AR is a significant advantage to its use. The three-dimensional images allow students to participate in the exploration of those concepts, becoming inspired by "learning by doing," or learning from experience, making the practical uses of science more relatable to students

(Yilmaz, 2021, p. 142). This type of real-world, practical learning is exceedingly important in science education, where teachers work to connect abstract concepts to relatable areas of student experience and daily lives.

Another key benefit of AR technologies in the science classroom noted by researchers studying the use of individual technologies in the classroom is their ability to be inclusive, allowing students to interact with the technologies across age levels, learning styles, and physical and mental capabilities. Yılmaz and Gözüm (2023) saw similar increased learning outcomes in kindergarten students learning about animals to those found by researchers studying student learning outcomes at increasingly higher grade levels (p. 140). Students engaging with AR technologies in science classrooms as supplemental material are afforded the opportunity to learn audibly, visually, and kinesthetically, making them effective for teaching many students of all learning styles (Barrow et al., 2019, p. 2). McMahon et al. (2015) found in a study of fourth-grade students with intellectual disabilities and on the autism spectrum had increased learning outcomes when engaging with AR to learn new science vocabulary terms (p. 10), while Wibowo et al. (2023) found in a similar study with students with physical disabilities that they were able to learn new vocabulary terms more easily when AR technologies were used as supplemental resources as a result of their increased access to engagement with materials (p. 7). Technologies which allow more students to be reached during individual lessons are of great value in modern classrooms with diverse student populations who learn in different ways and with varying abilities.

Increased learning outcomes are observed in post-test results following the presentation of science lessons using AR technologies in academic research. New and challenging concepts are more easily understood when visualized using these technologies (Al-Anazi & Khalal, 2022). Students are more likely to learn in environments in which they are interactive, a noted feature of AR technology exercises, which inspires the use of "higher-order thinking strategies" such as cognitive holding power (CHP), or the ability of students to involve themselves in first- and second-order thinking processes (Al-Anazi & Khalal, 2022, p. 1055). In a study of students using quick response (QR) codes, or codes which can be read by scanners and smartphones and used to interact with materials, pre- and post-test study data showed improved student outcomes due to the engaging and interactive nature of these technologies, which can be used both in the classroom and outside of it to prepare for lessons and explore subjects further (AlNajdi, 2022, p. 10). On post-testing, students learning using 3D sand tables were determined to answer questions more precisely using what they learned while interacting with AR (Moore, et al., 2020, p. 244). Increased learning outcomes in academic research studying the use of mobile technologies in combination with traditional teaching methods on middle-school students in Indonesia showed that learning outcomes were improved as a result of increased motivation for students engaging with the technology during science lessons, with scores post-test "significantly" higher for students who learned using supplemental AR technology (Maulana, et al., 2020). Increased outcomes are the result of the combined benefits noted across studies, where students exposed to AR in the science classroom consistently perform better than their counterparts who had no AR technologies supplementing their learning during science lessons.

Challenges presented in the use of AR in science classrooms were also recorded by researchers during these experiments. In each of the studies, attention to connectivity and failures in infrastructure were expected and, in most cases, resolved, but other challenges were also reported. Yilmaz (2021) recorded responses by students related to challenges of these technologies as the need for improving the quality and functions of these technologies as well as concerns about the amount of time the use of these technologies requires (p. 143). Students in this study also indicated that prior knowledge and preparation were important for students in the future in using these technologies, indicating that AR alone was not enough for teaching science effectively (Yilmaz, 2021, p. 143). In AlNajdi's (2022) study of students using QR codes to interact with materials, some students reported having limited access to technologies outside the classroom, thus limiting their ability to explore subjects further in the same ways their classmates did (p. 10). Radu et al. (2019) determined in their study that AR technologies were beneficial to a many of the students who participated in lessons on electricity and magnetism, but that other students fared better with more traditional teaching methods, indicating that the teaching of all natural science fields and topics may not benefit from AR, and that some students require more traditional learning methods to be combined with AR as a supplemental resource (p. 544). As the use of AR technologies in science classrooms increases, questions about how to best provide these learning tools to benefit students in the most effective ways rise to the forefront of education and educational technology research.

1.3. Aims

Through a review of recent and relevant literature around the use of AR as a tool in the science classroom for students of all ages, this research paper aims to provide a comprehensive understanding of how AR both benefits and challenges science teaching and learning through review, discussion and analysis of the latest research, studies, and experiments in this field. This research paper examines contributions that explore and delve into the integration, opportunities and challenges presented by AR technologies in science teaching and learning, and aims to address and identify the best practices for integrating AR technologies in the science classroom for the future.

1.4. Research Question

This paper explores the research question of what benefits teachers and other education experts have identified in the use of AR technologies in the science classroom as their use has expanded in the past ten years, what challenges the use of such technologies have presented, and how those challenges might best be addressed in the future. The research question was formulated using the PICOT structure (da Costa Santos, et al., 2007).
(P) Population: students of science across grade levels;
(I) Intervention: the use of AR technologies in the teaching of science;
(C) Comparison: students who had been taught science subjects with AR as a supplemental tool verses students who received no such supplemental instruction;
(O) Outcome: reported benefits and challenges identified by science instructors and education experts as well as potential solutions;
(T) Time: limited to a ten-year span of 2014-2024.

2. Method

Studies were gathered through searches on EBSCO Host, Academic Search Premier, Google Scholar, and ERIC using the search terms “augmented reality” AND “science” AND “classroom” and other combinations of these terms. Both quantitative studies which examined specific AR technologies used in the classroom and those based on observed and recorded data were included as well as qualitative studies in which teachers of science and experts in educational technology were interviewed or surveyed. Search results were narrowed by excluding systematic and scoping reviews covering articles prior to 2014, articles that included virtual reality (VR) technologies with AR to determine outcomes, studies of AR technologies for use in classrooms to teach subjects that did not include natural sciences, and studies published in languages other than English. Ten articles exploring the benefits and challenges of using AR to teach natural sciences– including geology, biology, physics, chemistry, anatomy, and astronomy – as well as potential solutions to those challenges were included for review in this study.

3. Results

Articles assessed for this study to determine the benefits and challenges of using AR technologies in science classrooms included studies performed in countries across the world with interviews, surveys, and other forms of data collection with hundreds of teachers and scholars of education focused on grade levels from pre-school to the university level of education.

Table 1: Teacher/Expert Feedback on AR in the Science Classroom

Author(s), Year	Location	Subject	Grade Level	Participants
Fearne & Hook, 2023	Great Britain	Science	Primary	57
Nielson et al., 2016	Denmark, Norway, the UK, Spain	Science	Secondary	35
Osadchyi et al., 2021	EU	Physics/STEM	University	Varied

Peikos & Sofianidis, 2024	Greece	Science Education	Pre-school/Primary	69
Perifanou et al., 2023	United States, UK, Greece, Malta, Australia, India, etc.	All subjects, particularly Science and Mathematics	Primary/Secondary/University	93
Atalay, 2022	Turkey	Science Education	Primary	41
El Kouzi et al., 2019	Canada	Science	Undergraduate	15
Demircioglu et al., 2022	Turkey	Science	Middle	79
Güntepe & Usta, 2021	Turkey	Biology	Primary	32
Marin-Diaz et al., 2022	Spain	Mixed	Secondary	350

Note. Studies included to determine benefits/challenges of AR in the science classroom.

Teachers and other educational experts reported a number of benefits related to using AR technologies in the science classroom. The benefits identified by these experts shared common themes related to preparing students for the future, visualization of abstract concepts and previously invisible processes, motivation to learn, inclusion, engagement, and collaboration, resulting in many cases in improved learning outcomes.

Table 2: Benefits Identified in Teacher/Expert Feedback on AR in the Science Classroom

Author(s), Year	Prep for Future	Visualization	Motivation	Inclusion	Engagement	Collaboration	Improved Learning Outcomes
Fearne & Hook, 2023	X	X	X	X	X		X
Nielson et al., 2016		X	X		X	X	
Osadchyi et al., 2021	X	X	X	X	X	X	X
Peikos & Sofianidis, 2024		X	X	X	X	X	X
Perifanou et al., 2023		X	X		X	X	X
Atalay, 2022	X	X	X	X	X	X	
El Kouzi et al., 2019	X	X	X	X	X	X	X
Demircioglu et al., 2022	X	X	X	X	X	X	X
Güntepe & Usta, 2021	X	X	X		X	X	X
Marín-Díaz et al., 2022		X	X	X	X	X	X

Notes: Benefits of Using AR Technologies in the Science Classroom Identified by Teachers and Other Experts

Six of the ten articles analyzed for this study mentioned using AR technology as a way of preparing science students for the future, where digital technologies are prevalent and growing rapidly in use. All of the teachers and educational technology experts surveyed, interviewed, and providing data through other methods indicated that the use of AR technologies in the science classroom benefits students by providing visual means for understanding abstract concepts and viewing processes and phenomena that would not be visible otherwise, motivating them to learn, and engaging them in ways that other methods of teaching and learning in the science classroom do not. Seven of the studies noted responses indicating that teachers and education experts feel that AR

technologies in the science classroom make lessons more inclusive, both in teaching across learning styles and age groups and providing access for students with mental and physical disabilities. Nine of the studies reported that the use of AR technologies in these classrooms allowed for more collaboration, and eight of the studies noted improved learning outcomes for students learning science in lessons including the use of these technologies in science classrooms.

Table 3: Challenges Identified in Teacher/Expert Feedback on AR in the Science Classroom

Author(s), Year	Cost	Confidence	Infrastructure	Quality	Safety/Security	Time	Other
Fearne & Hook, 2023	X	X	X			X	X
Nielson et al., 2016	X	X	X	X			
Osadchyi et al., 2021		X			X	X	
Peikos & Sofianidis, 2024	X	X	X			X	X
Perifanou et al., 2023	X	X	X	X	X	X	X
Atalay, 2022		X					
El Kouzi et al., 2019		X	X	X		X	
Demircioglu et al., 2022		X	X			X	
Güntepe & Usta, 2021		X	X	X			
Marín-Díaz et al., 2022	X	X	X			X	

Notes: Challenges of Using AR Technologies in the Science Classroom Identified by Teachers and Other Experts

Five of the studies included in this analysis noted teachers' and other experts' concerns about the cost of expanding the use of AR technologies in the science classroom, saying that budget restraints would prove a significant barrier to this expansion. The most common concern, with all of the included studies addressing the concern in some way, was the confidence that teachers express in their ability to implement the expanded use of AR technologies in their classrooms effectively. Infrastructure, which includes Wi-Fi capabilities and access to technology, was also a prevalent concern, with eight studies noting this response in answer to questions around the expanded use of such technologies in the science classroom. Four of the studies stated that teachers and other experts are concerned about the quality of available applications, which may hinder their ability to be educational or inclusive. Two of the studies noted educator and other expert concerns over the safety and security of expanded use of digital technologies in the classroom. Seven discussed concerns over the amount of time teachers have available for learning new technologies, focusing on science education in their classrooms, and introducing students to new technologies.

4. Discussion

A review of the literature reveals common benefits and challenges to the expanded use of AR in science classrooms, indicating that proposed solutions could be wide-ranging in addressing the challenges in schools around the world and across student grade levels. As the benefits of the use of these technologies in science classrooms makes clear, the need for addressing these challenges in order to deliver the best opportunities for students in these classrooms is imminently pressing.

4.1. Benefits

Using AR technologies in science classrooms for many students in the digital era has proven beneficial in a range of ways, ways too extensive to ignore when considering the future of science teaching and learning. Most

significantly, teachers identify a need to prepare students for the future through the use of new technologies like AR, the opportunities for visualization in a science learning environment that is afforded by AR technologies, increased levels of motivation by students to learn and interact with science concepts, the ability to teach diverse groups of students in science classrooms effectively, an increased level of engagement with materials and lessons, increased opportunities for collaboration through group work when using AR technologies in the classroom, and they note an improved student learning outcomes as a result of these benefits. (see Figure 1)

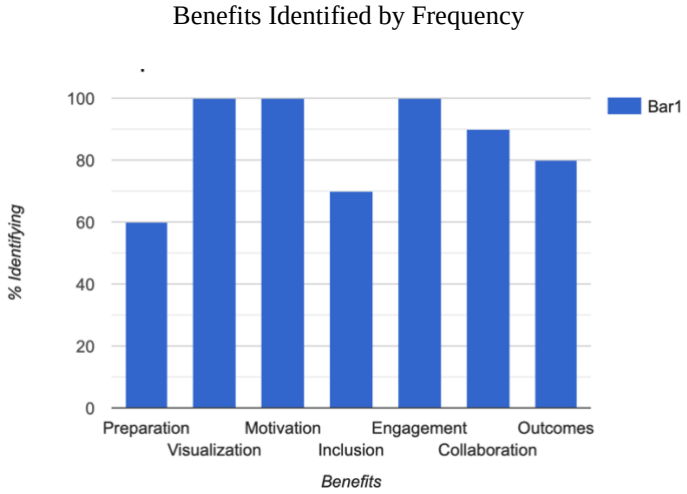

Figure 1: Benefits Identified in Teacher/Expert Feedback on AR in the Science Classroom by Frequency in Studies

4.1.1. Preparing Students for the Future

Several of the reviewed studies identified preparing students for the future as a benefit of offering AR technologies as a supplemental learning tool in science classrooms (Atalay et al., 2022; Demircioglu et al., 2022; El Kouzi et al., 2019; Fearne & Hook, 2023; Güntepe & Usta, 2021; Martin-Diaz et al., 2022). The digital age requires much of educators in preparing students for the future as productive workers and citizens. Students in the modern era often have a significant amount of exposure to digital technologies before reaching a science classroom, and their learning experiences require a combination of both traditional and digital experiences to be comprehensive in scope and to prepare them for use in the modern workplace, an ever-expanding and changing world in which technologies are increasingly more prevalent (Peikos & Sofianidis, 2024, p. 1). The digitalization of data, for instance, requires that workers in the fields of life sciences be well-versed in the use of technologies for gathering information, recording information, and completing tasks (Barrow et al., 2019). As evidenced by the rapid innovation in technologies in the digital age, preparing students for the future requires an extensive amount of interaction with digital technologies like AR in science classrooms.

4.1.2. Visualization

The ability to visualize abstract concepts and processes aids in increased comprehension in science classrooms (Atalay et al., 2022; Demircioglu et al., 2022; El Kouzi et al., 2019; Fearne & Hook, 2023; Güntepe & Usta, 2021; Martin-Diaz et al., 2022; Nielson et al., 2016; Oshadchyi et al., 2022; Peikos & Sofianidis, 2024; Perifanou et al., 2023). Lessons in the field of science are enhanced by AR as "augmented realities allow immersive and visual experiences for the user," allowing students to understand more abstract concepts because it allows for the interaction of different types of knowledge (Barrow et al., 2019, p. 2). Students using AR technologies are afforded an opportunity to "visualize" the lesson being offered in ways that have not previously been available. Particularly in the field of natural sciences, the opportunity for visualization is critical for learning, as it plays such a crucial role in developing an appreciation of structures, processes, and functions (Barrow et al., 2019, p. 3; Perifanou et al., 2023; p. 5; Peikos & Sofianidis, 2024, p. 9). Pre-school and primary teachers in Greece indicated that 3-D visualization aided comprehension of abstract concepts and biological and technological processes in innovative ways (Peikos & Sofianidis, 2024, p. 9-10). Teachers of students across primary and secondary grade levels in a

wide-ranging sample of instructors around the world identified the opportunity to visualize abstract concepts and processes as the primary benefit of AR technologies in learning (Perifanou et al., 2023, p. 5). Expert teachers from the UK, Denmark, Spain, and Norway also identified the ability to visualize that which was previously inaccessible to scientists (such as atoms or phenomena in outer space) or simply difficult to grasp in the absence of a three-dimensional visual aid as the most important benefit of AR in their classrooms (Nielson et al., 2016, p. 165). Primary and secondary students learning geography engage with a projection of a virtual topography and water superimposed over a real sandbox, allowing them to see depths and earth structures (Nielson et al., 2016, p. 161). Students in medical science classrooms can simulate surgical training or visualize abstract concepts in new ways using such apps and other technologies because of the ability to observe and examine projected three-dimensional structures (Barrow et al., 2019, p. 2). Medical and nursing students can visualize vital systems of the body using AR technologies in order to better understand their functions and improve practice, potentially achieving better patient outcomes (Nielson et al., 2016, p. 160). As academic research learns more about best practices in delivering science education, visualization of scientific processes and concepts will be key in determining which fields of science are best delivered through the use of AR.

4.1.3. Motivation

The ability of AR technologies to motivate students in science classrooms is an inordinate benefit to its use (Atalay et al., 2022; Demircioglu et al., 2022; El Kouzi et al., 2019; Fearne & Hook, 2023; Güntepe & Usta, 2021; Martin-Diaz et al., 2022; Nielson et al., 2016; Oshadchyi et al., 2022; Peikos & Sofianidis, 2024; Perifanou et al., 2023). Motivation to learn is key to increasing student outcomes, as Maulana et al. (2020) notes, saying that "the relation between motivation and learning is that motivation drives learning activities to achieve maximum learning outcomes…someone who has no motivation will do no learning activities" (p. 365). Teachers identify science weeks and science fairs as positive motivators for students, and the use of AR during such events to enhance demonstrations and visualize concepts and findings has been key to piquing their interest and motivating them to learn more about the topic or the subject more generally (Fearne & Hook, 2023, p. 337). Teachers responding to surveys by researchers indicate that they believe students enjoy AR activities and that they are more engaged with learning during participation (Oshadchyi et al., 2021, p. 12; Peikos & Sofianidis, 2024, p. 8). Since motivation is critical to learning, it is a benefit of AR that results in positive, enhanced learning outcomes in this field of study. One primary motivator related to the use of AR in science classrooms is the ability to connect science in the classroom to real life situations, where students complete practical activities that actively engage them (Fearne & Hook, 2023, p. 337). The practical activities, teachers report, make AR-inclusive exercises a form of "learning by doing," and twenty percent of teachers interviewed said that they believe such activities engage students at a higher level, and sixteen percent reported their belief that they enable them to "take ownership of their own independent learning" (Fearne & Hook, 2023, p. 337). Research has shown that study that includes practice is more effective and increases the quality of educational instruction (Oshadchyi et al., 2021, p. 13). Nursing students, for instance, report having a higher level of understanding of the respiratory system after using interactive AR technologies to explore them (Nielson et al., 2016, p. 160). The ability to engage with real-world problems, such as climate change, is also identified by teachers as a benefit which makes AR technologies practical and engaging for students (Nielson et al., 2016, p. 165). "Active studying" methods, rather than teaching solely through the traditional lecture method, are often preferred by teachers who use these methods effectively in classrooms, indicating that their use should be more widely encouraged, supported, taught, and resourced (Oshadchyi et al., 2021, p. 13). AR should not replace traditional teaching methods entirely, but its use as a supplemental tool can do much to motivate students to learn.

4.1.4. Inclusion

Another benefit to the use of AR in science classrooms is its versatility in reaching diverse groups of students, making it more inclusive for use in the classroom (Atalay et al., 2022; Demircioglu et al., 2022; El Kouzi et al., 2019; Fearne & Hook, 2023; Martin-Diaz et al., 2022; Oshadchyi et al., 2022; Peikos & Sofianidis, 2024). Surveyed primary and pre-school teachers (Peikos & Sofianidis, 2024, p. 1) indicated their belief that AR technologies have cognitive benefits that would enhance the learning of all students in science classrooms. AR technologies, for example, provide an opportunity to address the need to engage with students with a range of

learning styles. For many teachers, "the attractiveness of AR as a teaching tool is its ability to deliver a blended learning experience created from the mixing of the virtual and real environment or materials in the classroom" (Barrow et al., 2019, p. 2). AR technologies offer methods for integrating modern tools in the classroom that blend with more traditional teaching methods rather than replacing or upending them, allowing for "the blending of instructive teaching with digital visualizations" (Barrow et al., 2019, p. 2). AR technologies can be employed for group use instead of allowing only for individual use through a virtual reality headset, with AR technologies catering to a range of learning styles to be "mixed" in a single lesson as the technologies are combined with other teaching methods, providing a collaborative learning experience that fosters inclusion (Barrow et al., 2019, p. 2; Peikos & Sofianidis, 2024, p. 10; Perifanou et al., 2023, p. 6). Students with disabilities, for example, are afforded new opportunities to learn through the use of AR, providing opportunities for engaging with learning in ways that are more accessible to students, providing both visual and audible content, and are less overwhelming than instruction that includes a requirement to simply read and write for long periods of time in the classroom (Peikos & Sofianidis, 2024, p. 11). The use of AR as a tool in the classroom allows instructors to blend the real and the virtual with other teaching materials and methods for a more comprehensive experience in learning that is suited for a range of different learning styles and to meet the diverse needs of student learners (Barrow et al., 2019, p. 1). As the use of such technologies in the science classroom expand, the use of lecture-style teaching practices, a practice which does not best appeal to every learning style, will be supplemented and expanded through the use of more interactive forms of teaching and learning (Fearne & Hook, 2023, p. 330). As the use of AR technologies in the classroom expands, the benefits for students across a diverse range of learning needs can be addressed.

4.1.5. Engagement

Teachers and other education experts note an increased level of engagement with learning materials and lessons among students whose learning is supplemented by AR technologies in the science classroom (Atalay et al., 2022; Demircioglu et al., 2022; El Kouzi et al., 2019; Fearne & Hook, 2023; Güntepe & Usta, 2021; Martin-Diaz et al., 2022; Nielson et al., 2016; Oshadchyi et al., 2022; Peikos & Sofianidis, 2024; Perifanou et al., 2023). Barrow et al. (2019) reports that students who participated in his study of AR applications for learning about glucose metabolism and insulin signaling found it interesting and engaging, but that twenty-five percent also reported that they took fewer notes during the lesson, indicating that engagement with AR might require different methods of engagement with corresponding learning and comprehension activities (p. 5). Demircioglu et al. (2022) found that teachers and other education experts reported that students had an increased level of interest in science activities and concepts when supplemented with AR technologies during an astronomy lesson (p. 30). Forty-six percent of teachers and education experts indicated in surveys that they believed students were more likely to engage in science learning when AR was used to enhance lessons, a belief borne out by academic research (Marin-Diaz et al., 2022). The opportunity to interact with science learning provides ample area for students to engage with learning in the science classroom.

4.1.6. Collaboration

Teachers and other educational experts also widely identified opportunities for student collaboration as an essential benefit of using AR technologies in science classrooms (Atalay et al., 2022; Demircioglu et al., 2022; El Kouzi et al., 2019; Güntepe & Usta, 2021; Martin-Diaz et al., 2022; Nielson et al., 2016; Oshadchyi et al., 2022; Peikos & Sofianidis, 2024; Perifanou et al., 2023). In addition to offering visual experiences, AR technologies are interactive and collaborative, all of which are benefits science teachers identify as particularly useful for learning (Nielson et al., 2016, p. 165). Teachers referred to the AR technologies they had used in their classrooms or seen used in classrooms as both "student-centered" and "interactive," which indicates that lessons enhanced by AR technologies allow for collaboration in ways that best attend to individual student learning needs (Atalay, 2022, p. 38). The ability of AR technologies to "connect countless students in collaborative environments" is an important benefit of their use in the earliest science classrooms, from kindergarten students to those in advanced science programs (El Kouzi et al., 2019, p. 4). Collaboration is essential in science practice, and the need to teach science students to learn and explore science concepts collaboratively aids in preparing students to enter these career fields.

4.1.7. Improved Learning Outcomes

A majority of studies noted improved learning outcomes for students in science classrooms using AR as a supplemental tool for learning (Demircioglu et al., 2022; El Kouzi et al., 2019; Fearne & Hook, 2023; Güntepe & Usta, 2021; Martin-Diaz et al., 2022; Oshadchyi et al., 2022; Peikos & Sofianidis, 2024; Perifanou et al., 2023). Researchers have found that AR technologies are more efficient for learning than traditional lectures, multimedia resources, labs, and other learning activities used in the classroom (Perifanou et al., 2023, p. 1). Teachers identify the possibilities for situated learning in which students use critical thinking skills and kinesthetic abilities to engage with subject material as an attractive benefit to using AR technologies as supplemental tools in learning (Nielson et al., 2016, p. 165). Other teachers noted game-based, project-based, and inquiry-based learning as suited for aims in AR integration in the classroom, as well as story-telling, virtual labs, and other forms of learning activities (Perifanou et al., 2023, p. 5). Salmi et al. (2016) found that learning outcomes are often based on contextual variables such as prior knowledge and self-efficacy, but noted that "the results of this study provide evidence that interest in school science is enhance by situation motivation" (p. 263). Therefore, an increase in motivation to learn and engagement or interest in the material resulting from the use of AR in the science classroom can work to improve learning outcomes, although prior knowledge is more indicative as a predictor of positive learning outcomes (Salmi et al., 2016, p. 264).

4.2. Challenges

While the benefits of using AR in the science classroom are many and encouraging, barriers to the expanded use of such technologies in the classroom must be considered in any discussion of how to best move forward for the future. Expansion in this area will require significant financial investments, teachers lack training and expertise in advanced technologies which makes them reluctant to increase their use and hesitant to trust research noting the positive benefits of AR, school infrastructures providing internet access and equipment for the use of such technologies has yet to catch up to the digital age, the quality of many of the available applications are sometimes questionable, the safety and security of expanded internet usage make some teachers and educational experts leery to use them more expansively, the amount of time that teachers must invest in order to understand the technologies and explain them to students is a drawback, and other notable concerns arise in studies with this population of professionals. (see Figure 2)

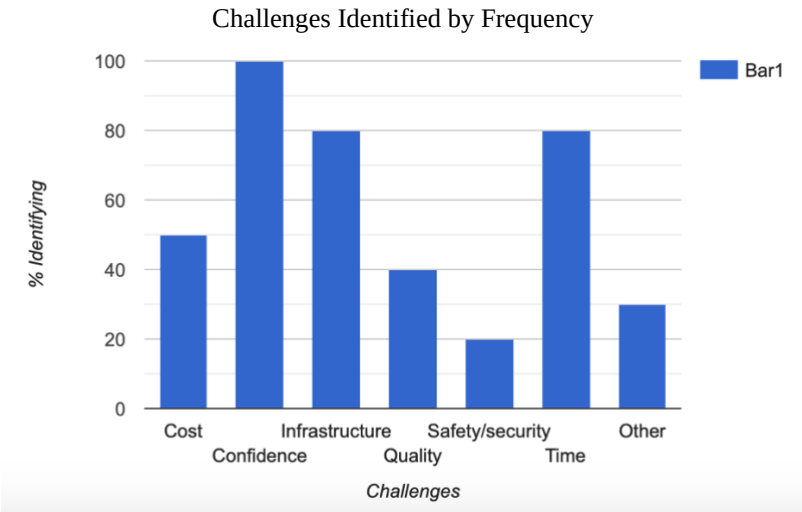

Figure 2: Challenges Identified in Teacher/Expert Feedback on AR in the Science Classroom by Frequency in Studies

4.2.1. Cost

While STEM subjects have become more emphasized over time as the need for skilled workers in these areas increases, many schools are well behind the curve in prioritizing such subjects, making progress toward the

increased use of AR technologies lagging. Another disadvantage to the need for expanded access to technologies in the classroom, particularly among populations of those of the low socio-economic status, is the cost of such technologies (Barrow et al., 2019, p. 2; Fearne & Hook, 2023, p. 333; Perifanou et al., 2023; p. 7; Nielson et al., 2016, p. 165; Oshadchyi et al., 2021, p. 12). Teachers note their concerns with the cost of such technologies considering that the budgets and resources afforded to school administrators are often too constrained to allow for widespread change in teaching tools and technologies for the classroom (Fearne & Hook, 2023, p. 333). In comparison to VR, which requires the use of costly head-mounted viewers that allow for only one user at a time, AR is considerably less expensive, as it can be accessed via mobile devices and stationary units as well as head-mounted displays (Nielson et al., 2016, p. 159). AR technologies, in this way, offer some answer to the problem of cost, as most students in modern classrooms already own smartphones; however, the "bring your own devices (BYOD)" model has its own disadvantages, as students commonly bring different types of smartphones and other technologies with them to classes with different operating systems, hardware specifications, graphic capabilities, and ease of use (Barrow et al., 2019, p. 2). Additionally, not all students own a smartphone, making students' ability to use such technologies both in and outside the classroom as an educational tool for study more limited, which further disadvantages students of low socio-economic status in areas where budgets and resources are more limited (Fearne & Hook, 2023, p. 333).

4.2.2. Confidence

Further, teachers in modern science classrooms often report having a low level of confidence in their ability to use and instruct students using AR technologies (Barrow et al., 2019, p.1; Oshadchyi et al., 2021, p. 12; Fearne & Hook, 2023, p. 335). In contextual interviews with teachers in Yorkshire, England, Fearne and Hook (2023) report that teachers expressed concerns after prior teaching technologies failed due to their limited understanding of them and stated that skills training was often lacking for teachers desiring to use and implement new technologies (p. 335). Teachers in some schools indicate that they are unclear how AR technologies can align with the national curriculum framework to improve instruction, indicating that the practice of integrating these technologies into the classroom has been neither emphasized nor explained in meaningful ways which can aid in achieving learning outcomes (Fearne & Hook, 2023, p. 336). This is the case despite the fact that a majority of teachers entering the field of science education in pre-school and primary classrooms (more than fifty-nine percent) indicate their desire to use AR in their classrooms, and all of the teachers in one survey recognized that AR was "definitely" or "probably" beneficial to students (Peikos & Sofianidis, 2024, pp. 8-9).

4.2.3. Infrastructure

The use of such technologies also brings with it the disadvantages related to system use and failures as well as difficulties in connectivity, with applications not always working as intended (Barrow et al., 2019, p. 6; Oshadchyi et al., 2021, p. 12; Perifanou et al., 2023, p. 7). Teachers of science in primary classrooms indicated their doubt that schools are "AR ready," as their schools' infrastructures are often outdated, leaving them ill-prepared for the common use of internet-driven technologies (Fearne & Hook, 2023, p. 335). Twenty-five percent of teachers surveyed in a range of areas in Europe identified technical barriers as one of the primary pitfalls of AR use in the classroom (Nielson et al., 2016, p. 165). Teachers in schools all over the world note that affordable AR learning tools can be costly and finding applications that are free for use or affordable in resource-strained schools can prove difficult (Perfanou et al., 2023; p. 7).

4.2.4. Quality of Applications

Other challenges identified by teachers were concerns about AR applications being unsuitable in design for use in the classroom, indicating that the quality of some of the available and affordable applications is less than desirable. For instance, some teachers indicated their concerns that the apps they used were truly collaborative in ways that are effective for teaching, with teachers given opportunities to interact with students or with students being given opportunities to interact with the application, and apps being truly intended for educational purposes rather than being "gimmicky," and with a focus related to a current issue in science (Nielson et al., 2016, p. 165). Additionally, only twenty-two percent of students in Barrow et al.'s (2019) study considered themselves frequent "gamers" with

significant engagement with AR technology outside the classroom, indicating that such applications are not currently designed with novice users in mind (p. 5). Concerns raised by these educators indicate that app developers are not versed in how science education is best delivered and should be designed with educational methods and goals in mind.

While concerns over cost, teacher confidence in their ability to deliver lessons using the latest technologies, infrastructure concerns, and concerns over the quality of available AR applications, a range of other concerns were also noted in these studies. Some teachers and other education experts noted concerns about safety, privacy, and security, as information leaks can threaten students and staff due to opportunities for the theft of personal data and identity theft (Perifanou et al., 2023, p. 7). Osadchyi notes the need for improved infrastructure to enhance security protections (p. 6), and an increase in security breaches in recent years, breaches which threaten critical infrastructure and user privacy, indicate that these concerns are well-founded (Madnick, 2024). The limited time allotted for science instruction in some primary classrooms, particularly in school districts and countries where English and math classes are prioritized over science instruction, makes allowances for the time to learn and use AR technologies less possible (Fearne & Hook, 2023, p. 329). The amount of time it takes for teachers to learn new technologies and understand how to use them to enhance science learning in order to achieve desired learning outcomes was also a concern noted by teachers in the field (Fearne & Hook, 2023, p. 329). Students also indicated in the study by Radu et al. (2019) that their learning would be enhanced by the inclusion of other resources and materials such as videos and traditional lectures, indicating again that AR technologies should remain a supplementary tool in science classrooms used in combination with other, more traditional methods of teaching (p. 544). Finally, the study by Radu et al. (2019) showed that some students learned particular elements of the subject they studied better in groups where AR technologies were not used, indicating that not all aspects of science learning are best explained using this method (p. 544). Further research as the use of these technologies expands will likely reveal new challenges for which solutions must be found.

4.3. Solving Challenges

In addition to insights into the benefits and challenges of the expanded use of AR in science classrooms, teachers and other educational experts offer a range of insights into how to best meet these challenges in the future. The approach will be multi-faceted and focus on reducing costs, strengthening infrastructure, supporting and training teachers, offering opportunities for collaboration between education experts and AR developers, and investments in technologies that benefit students in the science classroom. Models in several areas of the world provide the first guides to expanding technology use in the classroom, including AR technologies, through investments in infrastructure, and the need for further collaboration between teachers and educational technology creators is also key to meeting future challenges. Further, training teachers to understand and use AR in the classroom, beginning in pre-service and continuing throughout the age of expanded innovations in technology, is essential if the barriers to expanded use of AR technologies in the science classroom are to be fully addressed.

In several areas of the world, governments are preparing for the future by dedicating spending to expanded access to technology in education. The Strategy of development and informational society in Ukraine, Project Europe 2030, and Education 2030 Agenda, the computer systems using grid-and cloud technologies, including AR technologies, are included in the staged goals for the future of education, which "infers the formation of the new digital infrastructure and digital sphere reassessment," including in education (Oshadchyi et al., 2021, p. 12). In Saudi Arabia, investments in critical infrastructure as part of an initiative to improve educational outcomes have revolutionized science teaching, with an institutional site known as iEN providing AR applications, digital science textbooks, and virtual trainings (Al-Anazi & Khalal, 2022, p. 1057). This investment has yielded significantly positive results, including a faster and more streamlined process of moving learning online during the COVID-19 pandemic (Al-Anazi & Khalal, 2022, p. 1056). The Saudi model, as well as initiatives undertaken in other parts of the world, provide a useful framework from which infrastructure and other challenges might be addressed. As infrastructure improves, several other challenges, including time constraints and concerns over safety and security, will be addressed.

Educational programs, including those using AR technologies, must adapt and work with educational collaborators, improving systems and offering free access to students for classroom use (Oshadchyi et al., 2021, p. 12). Although smartphones, with built-in cameras for which AR apps are designed for use, provide a low-cost device through which such applications can be easily accessed by students of all ages, not all smartphones use these technologies in the same way, nor do all smartphones have the same capabilities in allowing for their use (Fearne & Hook, 2023, p. 329). Investments in both infrastructure and equipment will be critical if the expanded use of such technologies can be achieved. System failures and connectivity issues create further challenges for the use of AR technologies in the classroom, although these issues may well be resolved with further use and testing, particularly when scientists and instructors are called upon to provide feedback and specify how applications can best be structured for use with science student learning (Barrow et al., 2019, p. 6). The limited time for science instruction in many primary classrooms is especially problematic when these technologies fail or require significant amounts of time to employ and explain to students (Fearne & Hook, 2023, p. 329). As investments in infrastructure and training for teachers increases, the amount of time needed to identify, explain, and address connectivity and other issues related to internet use should also improve.

The need for increased teacher training to improve competency in delivering science instruction using the latest in digital technologies is crucial to expanding the use of these supplemental learning tools (Atalay, 2022, p. 38). Teachers are primarily educators and not technology experts, which means that training on how to use AR technologies in the classroom is much much-needed if the widely increased use of these applications to motivate students and expand their learning experience is to be realized, and instruction on how these technologies can be used to achieve curriculum standards should be included (Fearne & Hook, 2023, p. 338). Ensuring that teachers are fully equipped to use AR technologies as a supplemental educational tool in the classroom requires dedicated training to increase confidence and ensure that students are receiving the highest benefit from the technology (Oshadchyi et al., 2021, p. 12). In surveys, teachers identify digital skills that are both necessary and in need of development in the modern classroom, particularly in the fields of natural sciences and mathematics, for the newest technologies to be most effective, skills such as 3D modeling, design, and development, innovative pedagogy and instructional design, and basic skills related to AR instruction including digital and informational literacy, hardware use and proficiency, and e-learning techniques (Perifanou et al., 2023, p. 4).

Additionally, issues with applications being more collaborative and addressing current science concerns can also be addressed with communication between educators and application developers (Nielson et al., 2016, p. 167). The need for collaboration between teachers and educational AR technology developers is prescient in an age where such technologies are expected to rapidly expand in use in the classroom. Perifanou et al. (2023) refer to teachers as "catalysts in the educational process," making their input on educational interventions, including technologies, crucial for success in achieving educational goals (p. 1). In addition to providing training for teachers on the use of AR technologies, providing materials which correspond with these technologies and guide students is also critical for learning (Peikos & Sofianidis, 2024, p. 11). Such materials, teachers have noted, would enhance knowledge and enrich activities (Peikos & Sofianidis, 2024, p. 11). As the digital age continues, these are key areas of interest and note in the field of education sciences and educational technology, as the need to address the issues noted in this study is evident.

5. Conclusion

The benefits noted by teachers and other experts in the field of science teaching and learning of expanded use of AR in the classroom to supplement learning are reflected in studies with students using AR, providing a mandate that researchers in education cannot overlook. If the expanded use of such technologies is to be achieved, a multi-level approach is necessary. First, schools must be afforded resources in order to offer the most beneficial AR technologies to teachers in the science classroom as well as to improve infrastructure, making the opportunities to offer these technologies more wide-ranging. Second, science teachers must be offered continuing education sessions and training in the pre-service classrooms in order to facilitate a better understanding of how to best use AR to enhance learning, how AR can be used to achieve science outcomes, and how to work with diverse groups of students to ensure that all students benefit from this type of instruction. Third, students must be offered the equipment and resources that will allow them access to the most relevant and beneficial types of AR technologies

in the science classroom if the goals of education to prepare them for the future are to be realized. The demands of the digital age are pressing, and the future of education depends upon the level of support to be offered in advancing toward these goals.

One limitation of this study is the current limited use of AR technologies in science classrooms in many areas of the world. Only a small percentage of teachers in England (twenty-eight percent), for instance, reported having ever used AR in their science classrooms (Fearne & Hook, 2023, p. 336). With expanded implementation of AR in the science classroom and publishing of studies in educational sciences related to the use of AR in education, new insights into benefits and challenges, as well as solutions, will be revealed.

Areas of further research are plentiful, particularly as AR is an ever-developing technology for which ease of use and the widespread adoption of such technologies are still evolving. This review is limited to studies in a ten-year span during a time of rapid innovation in technologies; as new forms of AR for use in the classroom are developed, new studies into best practices and the benefits and challenges of their use will be required. Additionally, how to best offer trainings to teachers and opportunities for collaboration and development of AR technologies for the science classroom is an understudied topic that will need frequent and comprehensive updating as the use of these applications grow both in the classroom and in the career fields related to natural sciences. Finally, studies into the areas of science that benefit most from the use of AR technologies will provide a wide field of research opportunities in the future.

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