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Bridging the Gap: Augmented Reality for Math Education among Saudi Deaf Students

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ABSTRACT

Mathematics is often considered to be an important language, but for deaf students who are facing communication barriers, it becomes a tough language to understand the concept, even though a basic language. Therefore, to address this issue, the study aimed to investigate the augmented reality effectiveness of the mathematics education of deaf elementary students in Saudi Arabia. Using a pretest and posttest paired sample t-test; researchers employed the quantitative experimental research design. A sample of Al-Amel Institute for Deaf Students in Al-Ahsa Province 60 students selected, who were enrolled in a class on the concept of circles chosen for the study, divided into two groups: an experimental group that received mathematics education by using AR and a control group that traditionally received education. The results revealed a significant improvement in posttest scores of the experimental group as compared to the control group, indicating that augmented reality has a positive impact on mathematics learning of deaf students in Saudi Arabia. The findings suggest that AR can be an effective tool in enhancing DHH students' mathematics learning because the scores showed significant improvement in the sample t-test for understanding geometry. Positive feedback from participants further highlights the potential of AR to revolutionize math education for deaf students. Therefore, AR tools must be incorporated into the special education curriculum that facilitate their visual and interactive learning experience.

1. Introduction

Deafness often creates unique challenges for children, particularly in acquiring essential life skills, building social connections, and achieving academic success. One of the most significant barriers is that many deaf children begin their educational journey without foundational skills, which places them at a disadvantage compared to their hearing peers [1]. Similarly, researchers emphasized that deaf students' academic performance is affected by the disparities in reading comprehension and overall development [2]. Although these challenges does not deeply rooted in intellectual capabilities, deaf students possess strong cognitive skills than their hearing peers are often linked to unsuitable curriculum, ineffective teaching strategies, and a lack of properly trained

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educators, which can leave them academically lagging behind their peers by as much as three grade levels [3]. To address these prevailing challenges, the role of technology has become increasingly significant.

Digital technological tools have provided new opportunities for making education easy and comprehensive, particularly for deaf students [4]. These technological tools played an integral role in removing the communication barriers, like as the need to learn sign language or interacting with those who are unfamiliar with it [5]. Similarly, various methods such as lip reading and sign language also helped many DHH students who faces challenges to access the content that is not specifically designed for them [6]. Moreover, the majority of classrooms lack skilled teachers and professional interpreters limits their prospects for social and academic growth [7]. Therefore, the development of digital technologies provides an integral solution for improving the accessibility of deaf students in their academic activities in order to overcome these consequences. For instance, mobile learning apps, web-based platforms, and video resources designed particularly for students have improved their educational experiences [8]. Among these technological advancements and innovations, augmented reality (AR) is considered a highly promising tool [9]. Therefore, this study explored how AR can improve learning outcomes for deaf students.

Previous studies have shown that AR technology, like 3D animations, can improve the learning of the students through providing a virtual element, and providing an environment that reflects the real world [10]. This helps to understand the student a difficult concept in a more easy way through a visually interactive and immersive manner [11]. In contrast to the virtual reality provided by a digital environment, AR experiences the gap between physical and virtual methods , which helps to make learning more grounded and is applicable to real-life situations [8]. Furthermore, AR also helps to increase social interaction and communications, including the sign language particularly for the deaf students [12]. Similarly, incorporating AR into the classroom fosters diversity and increases these kids' access to and engagement with the learning process increase the academic success of the deaf students [8]. Therefore, integrating AR into educational settings, there is significant potential to bridge learning gaps among deaf students in the field of mathematics.

AR is an integral tool for the mathematics students because the consistent of use of AR in the mathematics increase their potential to change how the abstract ideas are being to be taught [13]. There are various studies have been conducted in the field of mathematics where they found that AR makes math more engaging and interactive, allowing students to see how concepts apply to everyday life, which makes learning more enjoyable and effective [8; 13; 14]. [15] also enforced that AR helps students by making abstract concepts more visible and concrete, which greatly benefits their learning. Similarly, [13] reveal that AR enhances deaf students' understanding of geometry, while according to [16], AR) products, such AR-Books and smartphone applications, improve understanding and memory of fundamental mathematical skills. These studies emphasized that AR is an integral tool in mathematics which providing an interactive experience that is helpful for students who want to learn mathematics. Therefore, the study focused on exploring the role of AR on mathematics deaf students.

Seeking the importance of AR for the deaf students learning, prior studies still consisted on various gaps that need to be addressed in the present. At first, there are various researches have been investigated on AR on the mathematics students to increase their learning but these studies have limited attention on the deaf students [8; 13; 14; 17-19]. Therefore, to overcome this limitation, this study focused on the impact of AR on the mathematics learning of deaf students. Secondly, previously various studies have been conducted on the mathematics to improve the learnings of the students through making concepts more visual and interactive, but there's a need for learning materials that cater specifically to the language and learning needs of deaf students [20;

21]. Thirdly, various studies have also been conducted on other countries on the AR field in education but there are not enough research on how students in Saudi Arabia respond to and use AR-based math tools [22-24]. Therefore, this study fills a gap with a specific objective to examine the effectiveness of AR on mathematics education of deaf elementary students in Saudi Arabia.

This study provided both theoretical and practical contribution in the context of deaf students' academic performance in Saudi Arabia. Theoretically, this study extend existing literature by investigating the effectiveness of augmented reality (AR) in addressing the communication, linguistic and cognitive needs of deaf students for mathematics education in Saudi Arabia an area that remain unexplored. This study emphasized the role of AR in facilitating deaf students to visualize, supports the principle of Universal Design for Leaning (UDL) the promote multi-model and flexible teaching style based on students learning needs. Moreover, this contributed theoretically by proving how AR tools in mathematics education can bridge the gaps for deaf or hard of hearing (DHH) student groups. Practically, the current study offers significant insights to policy makers, educators, and curriculum designers by highlighting the potential of AR tools in mathematics training to improve academic achievement and commitment among deaf students. Furthermore, it promotes the application of accessible and interactive teaching tools as per the sensory strengths of deaf students. Lastly, this study contributed to creating a learning environment where all students can succeed, regardless of hearing ability in mathematics training.

2. Literature Review

Augmented reality (AR) technology has long captured the imagination of researchers and teachers. The journey began in 1974 when Ivan Sutherland introduced an innovative prototype, similar to a helmet equipped with lenses, so users can see the real world with three-dimensional forms [25]. In 1975, this work was expanded, with the intensive exploration of AR technology and the challenges published [26]. Since then, AR has in particular made significant progress since the 1990s, when the applications and potential acute are discussed [13]. Augmented reality adds digital details to the real world, making learning more interactive and valuable ¬¬¬¬, unlike virtual reality, which creates a whole new world, augmented reality enhances what's already there [27]. Including AR in education creates an attractive and effective learning environment. This technique improves the teaching experience by introducing virtual data in the contexts of reality so that students can interact with abstract concepts in a spontaneous and meaningful way [28]. Tools such as PCs, tablets, and smartphones are integrated into daily life, AR has emerged as a prominent tool in modern education, such as dynamic education for long learning.

AR used in the education allows to the students to increase their learnings through the interactions of virtual objects which is making learning more attractive and helps them understand complex concepts better [14]. This idea is supported by Vigotsky's social development theory, which states that students learn the best with guidance and support [29]. The difference between students acts as an accessory that they can do on their own and what they can achieve with help [30]. In mathematics, the students help to imagine abstract ideas, such as sizes and equations, and discover them in real time, leading to a deep understanding [31]. In addition, students with different types of learning requirements, which cause hearing loss, can benefit from AR [14]. It makes a useful tool for the improved reality (AR) to present the material that is easy to understand [32]. The cognitive principle that the major of Multimedia learning suggests that students are best learned when information is presented in both visual and interactive methods [33]. The AR makes 3D models, animations and lessons by mixing this, helping deaf students to understand the concept of mathematics. In addition, other studies have shown that AR learning environments can improve motivation, confidence, and educational performance in students with special requirements [13;

34].

Similarly, the AR can mix particularly real and virtual elements, which promotes real-time interaction and links students through visually rich materials [35]. Unlike virtual reality, it provides digital visual images of real settings for the world, providing a solid and available learning experience. AR also contributes to the revolution in education for individuals with disabilities, such as those who are hard of hearing or deaf, by offering new and innovative ways of information access. [36]. DEF students often face specific challenges, especially in an environment that prefers the spoken language or when they learn sign language [37]. AR helps to remove these challenges, and provides an immersive and interactive experience that deaf students tap in strong views on students [38]. AR-Technology combines visual signals, and gestures with everyday objects and settings so that deaf students can practice symbolic language and interact with educational materials in a more attractive and interactive way [31]. These previous investigations highlighted the importance of AR in improving student learning, especially for deaf students.

Along with theoretical importance, various empirical studies have been conducted on the AR. For example, [39] found that improving the AR in the education increase the learning skills of the students through the 3D visuals and animations particularly in the science and mathematics subjects where the aids through visualization is important to understand the difficult concept. Same results has been also found by [40] where they found that AR tools boosted engagement among Deaf and Hard of Hearing learners by offering interactive visualizations of math concepts that are frequently challenging to understand through traditional teaching techniques. [41] also highlighted that AR interventions have a positive impact on academic achievement, motivation, and engagement, making learning more accessible and successful for students. [39] also supported the view that incorporating AR into textbooks allows DHH students to interact with content independently, leading to increased cognitive engagement and self-paced learning. These previous all author's studies highlighting that AR is an important factor to enhance the students' learning skills. They also emphasized that further could be conducted on the developing countries that could increase the generalizability of findings especially on deaf students.

In addition, [42] research also found that AR could also helped to increase the collaborative learning within the deaf students through improving the communication skills. The also highlighted that AR allows for real-time interaction with classmates and teachers. They further recommended that institutions should focus on the simulations because the AR simulations become a useful tool in vocational training, which provides students with practical experience in a safe and supervised setting. [43] highlighted the same view and focused on the implementation of AR, which can facilitate remote learning. [44] research also highlighted the challenges faced by teachers of deaf female students in Riyadh, emphasizing that insufficient financial support was the biggest obstacle to implementing AR in classrooms. In another study of [45] also found that AR increases classroom management, which helps to increase the students' focus on the improvement of math problems, which increases their learning skills. Alruwaili's study highlighted that AR tools tailored to the Arabic language and Saudi cultural context led to increased engagement among learners in Saudi Arabia. These findings indicate that culturally sensitive AR design is crucial for effective educational implementation. While international research has shown AR's positive impact on DHH students, there is a notable lack of regional studies on this topic. These previous studies highlighted that AR is an crucial factor to increase the learning skills of the students. These studies also highlighted that further research could be conducted on other countries to increase the variations in the findings.

Further empirical studies have been conducted on the AR in educational surroundings through experimental designs with a pretest and posttest. These designs provide specific evidence of learning benefits responsible for AR interventions. For example, [46] conducted a semi-structured

study using the AR. A significant improvement has been shown in the posttest analysis. Similarly, [47] implemented an AR path using a mobile application. Their pre-test and post-test design reveal that students using AR tools scored much higher after testing in traditional learning settings than their peers, indicating better ideological understanding and engagement. In the context of mathematics teaching, [48] conducted a study with pupils in secondary school, where an AR-supported environment was implemented to learn geometry. The advantages of the AR group were statistically different between the pre-testing and testing results, demonstrating AR's capacity to enhance comprehension of geometric ideas and spatial skills. In addition, [49] made a systematic review of AR in education and found that most of the studies report before and subsequent test designs that report positive learning consequences that use the designs for before and subsequent tests, especially in science, mathematics, and language training. They emphasized that AR's interactive and engaging features contribute to better academic achievements, inspiration, and meditation. [50] also emphasized that AR is especially beneficial for students with hearing impairments, as it addresses their challenges in language comprehension, vocabulary, and cognitive development by offering a visually engaging medium. These previous studies emphasized that AR implementation in the posttest process increases the learning skills of the students. They also argued that further research could be explored on other developing countries to increase the scope of the study.

Despite the significant advancement of AR for improving the learning skills of the students. Still, the extant literature remains silent on empirical studies focusing on AR in the mathematics field, especially in the context of Saudi Arabia, which indicates a need for more localized and subject-specific research in this domain. Therefore, to address this gap, the current study intends to assess how well augmented reality (AR) might improve the educational experience for Saudi deaf students, specifically in mathematics, by making abstract concepts more tangible and comprehensible.

3. Method and Respondents

The aim of this study is to assess how effective augmented reality (AR) can be in enhancing the mathematical learning experience for deaf students. The study followed experimental pretest-posttest research design to compare actual academic performance between students exposed to AR instructions and those taught by using traditional learning models. This study conducted at the Al-Amel Institute for Deaf Students in Al-Ahsa Province. The study population involves all deaf students of the institute. The technique utilized to select participants is purposive sampling. Eventually, 60 students chosen for the study those enrolled in a class in the concept of circles divided into two groups: experimental group constitutes students those taught by using AR tools and control group involves students taught by using traditional methods. A total of 60 participants (30 in the control group and 30 in the experimental group), aged between 9 and 12 years, took part in this study. The participants were randomly assigned into two groups: experimental and control. Initially, mathematics questions developed to test students understanding about its foundational concepts. Before pretesting, questions reviewed and validated by specialists and experts and fewer adjustments made based upon their feedback. After that, the conducted a trial version after obtaining the information to test the validity of the instrument. After all steps, the reliability of the test estimated by using the Kuder-Richardson formula (KR-20), yielding a high reliability score of 0.875. Therefore, the test questions declared reliable.

For deaf students, in mathematics, geometry is a very difficult concept, especially circles. Due to which before adoption of the augmented reality (AR) learning model a pretest given to measure the students' initial understanding of circles. To familiarize DHH students with mathematical concepts, they were taught the concepts of circles by using AR tools over the five lessons that enable them to

explore key elements and definitions in detail. However, at the end of fifth lecture, post-test conducted to examine how much the deaf students had learned concepts of mathematics. The findings of the tests were presented by using descriptive and inferential statistics. The performance level of DHH students was categorized using descriptive statistics, and the pretest and posttest results were compared using inferential statistics. The Kolmogorov-Smirnov test was used in the study to confirm that the data was normal. Additionally, a paired sample t-test using SPSS software is used to assess the efficacy of learning models.

The recent study provided quantitative categorization of achievement level of deaf students. It shows students scoring 90% considered to achieve "very high" success and students who score between 70% and 89% were classified as "high" achievement. These summarized form of these categories presented in Table 1

Table 1
Deaf students learning results categorization Rate

Learning Outcomes	Categories
90%≥	Very high
70- 89%	High
50- 69%	Average
30-49%	Below average
10-29%	Low
9% ≤	Very Low

4. Study design

The researcher developed an innovative learning model by using augmented reality (AR) tool as its underpinning. This learning model built upon the concept of "tangible interface" where physical objects interact with virtual world connected to mathematical models. By mixing both virtual and real world, this model facilitates students to interact with abstract math ideas in a hands-on and meaningful way. Additionally, these model emphases on increasing students' cognitive abilities, especially their mathematical concepts understanding. Figure 1 depicts the activity flow of AR-based model, highlighting how the various elements of AR combine to create an interactive and engaging learning experience.

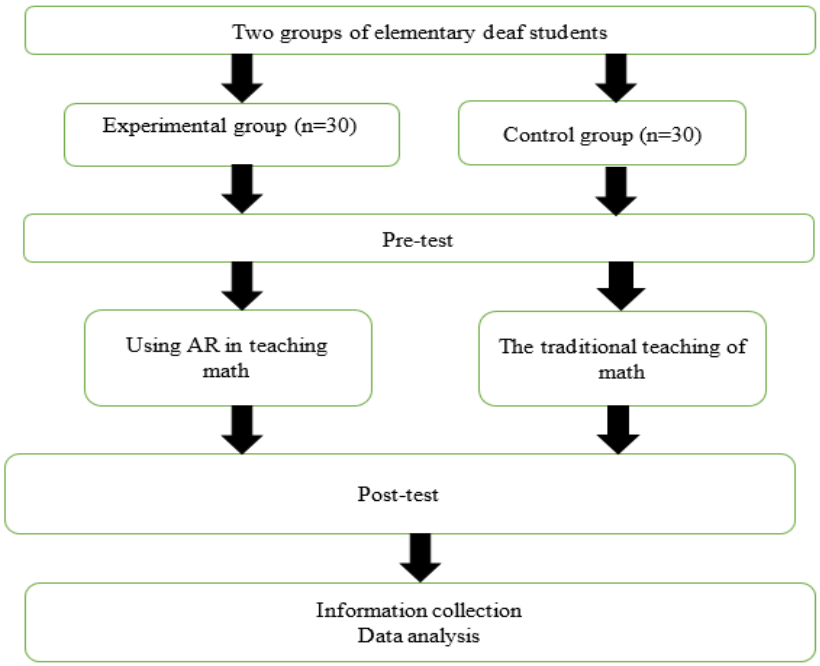

Fig.1. shows the activity flow for the augmented reality-based learning model.

5. Analysis and Results

5.1 Development of interactive math teaching materials

Many studies have shown that deaf elementary school students often struggle with topics such as graphics, numerical operations, sequences, fractions, geometric shapes, and matrices [34; 51-53]. Based on existing body of knowledge, these areas can be challenging particularly for deaf or hard of hearing (DHH) students. To address this, the researchers developed educational material using the improved reality (AR) technology. The work was a collaboration between two experienced mathematics coaches, each of whom had more than five years of teaching skills. Together, they created an interactive ARmatematics app using Unity 3D and Wuforia SDK. The Unity 3D is a versatile game engine that supports a wide range of platforms, including Windows and Android, making it ideal to design AR and VR applications. The app focuses on mathematical problems using a mixture of fried and second basic operations, while avoiding word problems to prevent heavy students. Researchers created this learning model around an AR framework inspired by the term "concrete interface", where physical objects are used to modify and interact with virtual elements. This framework addresses the special cognitive needs of deaf students by helping abstract mathematical ideas for practical experiences.

The result of this effort is an engaging, guided AR Math Application that students can download to their mobile devices. The app features an intuitive interface with interactive instructions, allowing students to explore and learn math concepts through hands-on experiences. This approach not only makes learning more enjoyable but also enhances their understanding of the subject. Figure 2 displays the app's interactive features, with specific functionalities tailored to various learning modules.

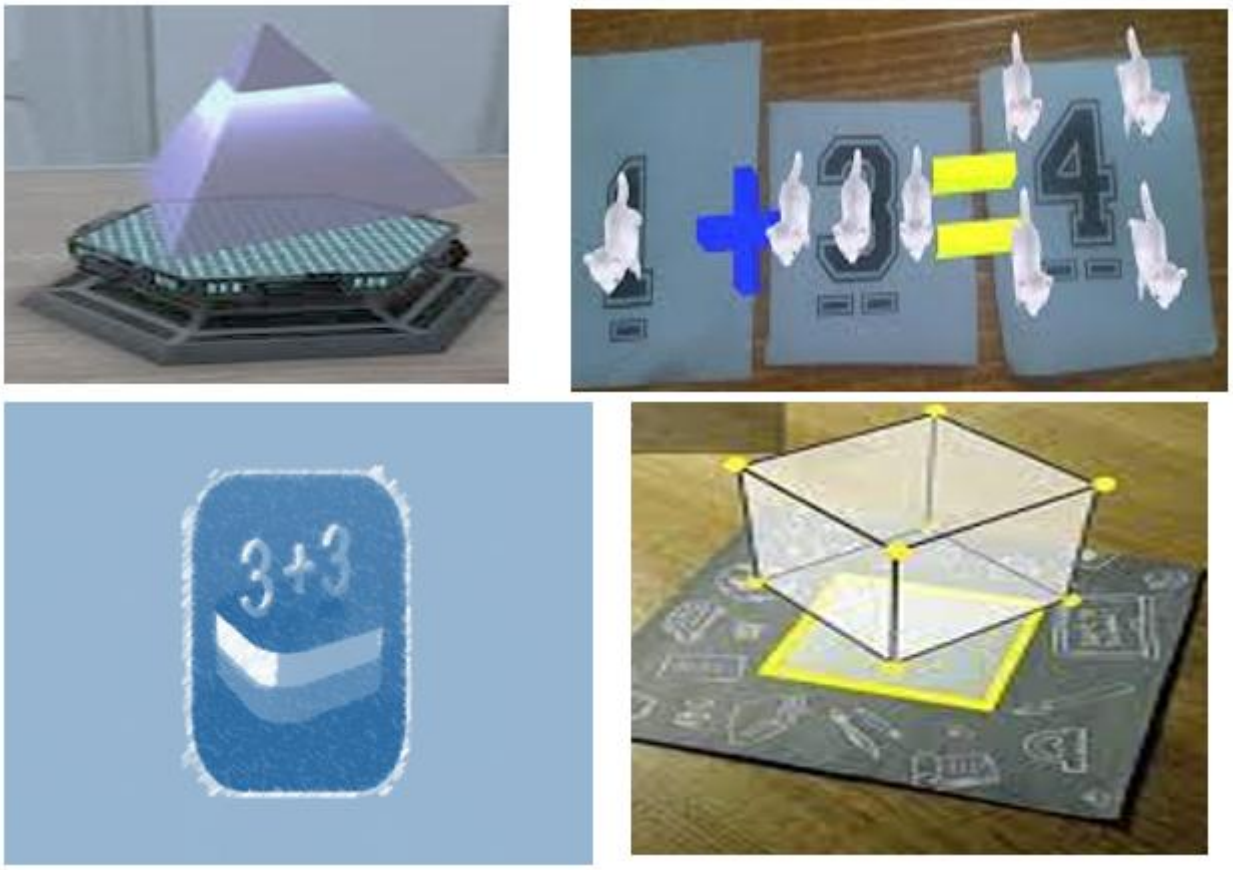

Fig.2. Multimedia effects of AR math learning for deaf students' app

5.2 Building a model of learning with distinct steps

Physical objects have been introduced in the initial stage. Deaf students are encouraged to get specific ideas in the context by examining and interacting with physical objects around them, particularly geometric figures and group arithmetic procedures. In the next stage, students organize the abstract ideas they have uncovered. This process includes conversations about the characteristics and elements of addition, subtraction, multiplication, and division, along with circles, squares, and triangles found in the items they studied. Now, students start to comprehend the abstraction after their exploration of objects, facilitating the formation of knowledge frameworks that represented visually. In the third stage, the instructor aids students in expanding their comprehension of the physical items they have investigated, relating them to other relevant situations. Students and their teams then evaluate and reflect on the learning results from the prior stage to tackle proactively any possible misconceptions in linking contextual knowledge. In the end, students synthesized the knowledge acquired from analyzing actual objects into condensed concepts based on their comprehension. Collectively, these strategies facilitate DHH students in the classroom to reach their goal of improving students geometrical and mathematical understanding by enhancing their interaction, engagement and understanding of the real world.

5.3 Learning Achievement Analysis

An independent sample t-test was performed to compare the math pretest scores in order to ensure that the two groups of deaf children started at the same level prior to the AR learning activity. The findings show that controlled group averaged 66.31, whereas experimental group averaged 66.11. This slight difference was not statistically significant ($t = 0.441$, $p > 0.1$), confirming that both groups had comparable foundational math skills before the experiment began. Next, to analyze the learning outcomes, the researchers examined the post-test scores to determine if the experimental and control groups varied significantly.

A fair comparison was ensured by using an analysis of covariance (ANCOVA) with pre-test scores as a covariate. Before proceeding, tests conducted to confirm the assumptions required for this analysis. The homogeneity of regression coefficients test showed that the relationship between pre-test scores (covariate) and post-test scores (dependent variable) was consistent across the groups ($F = 0.584$, $p = .421 > .05$). This allowed the researchers to move forward with the covariance analysis.

In Table 2, After adjusting for pre-test scores, the results showed a substantial difference in the groups' post-test scores ($F = 4.422$, $p = .036 < .05$). The experimental group, which used the interactive AR math app, had an average post-test score of 74.77 with a standard deviation of 14.78. In contrast, the average score for the control group, which used conventional teaching techniques, was 70.68 with a standard deviation of 21.44.

Therefore, the use of AR math apps improved deaf students' learning results when compared to traditional training, highlighting AR's effectiveness in enhancing math education.

Table 2
ANCOVA Test Results for Post-Test of Study Groups

	N	M	SD	A D	SE	F	sig
Experimental group	30	74.77	14.78	75.44	2.16	4.422*	0.036
Control group	30	70.68	21.44	70.35	2.55		

A D= Adjusted Mean, SE= Standard error of the mean p<.05

The study conducted a paired sample t-test to compare students' math learning outcomes before and after the intervention. Mentioned table 3, provides deeper insight into the effect of AR-based teaching approaches on deaf students' academic performance. The findings in Table 3 show

a notable increase in students' math achievement, as evidenced by the comparison of pretest and posttest scores. The results show a significant difference between pre-intervention and post-intervention performance, with a 2-tailed significance value of 0.000. These findings emphasize the important role of the model for learning the improved reality in increasing mathematical achievement in deaf students.

Table 3
Paired Sample t-Test Results for Math Learning Outcome.

		M	SD	SE	95% Confidence Interval of the Differences		T	Sig
Pair1	Pretest	55.43	6.334	.922	Lower	Upper	16.98	.000
	Posttest	75	8.742	.133	-18.96	-14.63		

6. Discussion

The study aimed to investigate the effectiveness of augmented reality on mathematics education of deaf elementary students in Saudi Arabia. The study selected the ANCOVA model to conduct the analysis and reported its results. The results of pre-test reveal that there is no significant difference in two groups control and experimental. This shows that there was no change in the relationship before formulating any intervention. These findings are supported by the study of [54]. On the other hand, after the intervention from the researchers, there has been shown a significant difference was shown in the ANCOVA results in the post test scores of post-test scores, which were using the AR-based math applications. The result has been aligned with the study of [46; 55] where they highlighted that AR increases student engagement, motivation, and understanding of abstract mathematical concepts. This is further aligned with the study of Shaaban and Mohamed [47], where they were also signified that AR technologies can improve academic achievement, especially for learners with disabilities, by providing interactive and visually rich content. These findings emphasized that teachers should employ the AR because the improving performance of the experimental group is emphasizing that AR can be a important educational tool for deaf students in facilitating to increase their understandings and gaining higher achievements in the mathematics.

Further paired sample T test results showed a valuable increase in the achievement of student's results in mathematics, which reflects a notable increase in mean scores from the initial pretest to the final posttest. This outcome indicates that incorporating the AR could become an integral part of improving understanding of complex mathematical concepts. The highly significant T value also confirmed that increasing academic performance could be attributed to the unique strengths of AR tools, particularly their interactive and visual features. These tools bridge the gap between the virtual and real worlds, providing students with a clearer understanding of abstract material that conventional methods often struggle to communicate effectively. The results are aligned with the previous study of [52] where they highlighted that the efficacy of AR in the education model could help to boost geometric comprehension in the deaf students. This is also further supported with the view of [56], who found that AR games could be used as an important tool in creating a more effective math learning experience for deaf students. In the same vein, Chao and Chang [57] study showed that AR technology can increase student engagement and motivation in math classes. Together, these studies highlight the transformative capacity of AR in education to enhance the learning experience of mathematics for deaf students in Saudi Arabia, improve commitment, access, and understanding. This adoption can also increase students' educational results.

In addition, the results after the test showed a significant improvement in the results that have been adapted to the study of Nunes [58] where they highlighted a various difficulties among the students in their hearing impairment encounter in the their mathematics learnings. Such kind of

difficulties are being frequently tied various constrained which are being imposed from their hearing loss which could impede different aspects in student knowledge acquisition, social skills, language development, vocabulary expansion, and literacy skills. Additionally, deaf students often depend significantly on assistive technologies to bridge the gaps created by this challenge. The integration of AR into teaching practices resulted in a more immersive and captivating learning setting, which in turn, generated increased student interest and motivation. AR's capacity to connect abstract mathematical ideas to real-world applications renders it an innovative and effective method for teaching mathematics [34; 59]. This approach improves individual learning outcomes by promoting collaborative efforts by initially merging virtual and physical components. This approach enables both individual and externally effective collaboration by mimicking the nuances of face-to-face interaction compared to traditional screen-based approaches. Ultimately, AR works as a powerful resource that can present more inclusive, relevant, and significant to learn to learn mathematics, providing them with opportunities to succeed that cannot be provided by traditional teaching methods.

Based on the above findings, it is strongly suggested that the educational institutions in Saudi Arabia should integrate the AR into their teaching practice, especially for students with hearing loss. The significant improvement seen in the score after deaf students using AR-based mathematics applications could emphasize the efficiency of tackling the unique challenges these students face in gaining mathematical knowledge. It has been emphasized by Lah et al. [60] by hearing stored students are being often face various obstacles in the their learnings due to language development, reading skills and boundaries in communication. AR helps remove these obstacles by providing visually rich, interactive and engaging learning environment that supports individual and collaborative learning. With a view to promoting inclusive and high quality education for Saudi educational institutions, integration of AR can be a transformative step towards improving the results of learning, and ensuring that all students are equal opportunities to succeed in topics as people with special requirements.

7. Theoretical and Practical Contributions and Future Directions

Various theoretical and practical contributions have been highlighted in this section. From a theoretical view, this study contributed significantly literature in understanding how deaf students' education can be improved through the integration of AR. The findings contributed significant findings in the context of Saudi Arabia, which has received limited attention in the extant literature. Furthermore, this study also contributed significantly literature by investigating the AR through highlighting how AR's capacity provides customized visual and interactive support that addresses the unique needs of these learners. Additionally, findings also contributed to highlighting the significance of AR for special education for emphasizing in this field. Current study also contributed to highlighting the socio-cultural factors importance in the students learning through signifying that AR content helps to the local context and language significantly improves accessibility and relevance for deaf students in Saudi Arabia. This study confirms the theoretical perspective that effective technology integration in educational settings is contingent upon various contextual factors, such as curriculum alignment, institutional readiness, and user training, highlighting the need for a comprehensive approach to technology adoption.

From a practical point of view, this study provides the necessary recommendations for teachers, direct designers, and decision makers who aim to improve mathematics education for deaf students through the use of AR technologies. Saudi Arabia's educational institutions should prioritize the development and implementation of visual-based teaching equipment that meets visual learning and sign language integration, and increases the ability of deaf students to connect and understand

with mathematical concepts. The Saudi educational reference requires collaboration between software developers, teachers, and specialist experts to ensure that the material is culturally relevant and linguistically accessible. In addition, this research emphasizes the requirement for strong infrastructure, including digital units with high damping and a reliable Internet connection to facilitate effective integration of AR-based instructions in academic environments. Institutions should use response systems that allow students to contribute to the evaluation and development of AR tools, which promotes a user-centric view for continuous improvement and processing. By implementing these approaches, Saudi Arabia can make significant advances to realize its vision 2030 goals for inclusive and technology-competent education, which can reduce educational differences for deaf students and improve their overall academic performance.

Various limitations have been highlighted in the current study along with significant contributions. The study was limited only on mathematics students, which limited the scope for other computer science students where symbolic or other development is a major part of their study. Therefore, future research could be conducted on other computer students to increase the research generalizability. In addition, the study is limited only on deaf students while other students are blind, and this study finding limit the scope for blind students. Therefore, future research could be conducted on other students to increase the study strength. Lastly, a study conducted on the pre-test and post-test process, while ignoring regression analysis, limited the study scope. Therefore, future empirical research could be conducted on regression analysis after adding other variables, which could increase the study scope.

8. Conclusion

The study aimed to examine the effectiveness of augmented reality on mathematics education of deaf elementary students in Saudi Arabia. For this purpose, two control and experimental groups from Al-Amel Institute for Deaf Students in Al-Ahsa Province were selected. The sample included 60 students enrolled in a class on the concept of circles chosen for the study, divided into two groups: an experimental group that received mathematics education by using AR and a control group that received education in a traditional way. The findings showed that the experimental group's posttest scores significantly outperformed those of the control group, suggesting that augmented reality benefits Saudi Arabian deaf students' learning of mathematics. According to the results, AR may be a useful method for improving DHH students' understanding of mathematics. Using a paired sample t-test, their scores were examined, and the findings revealed a significant improvement, especially in geometry comprehension. Participants' positive comments further emphasize how AR has the potential to transform math education for deaf students. Therefore, AR tools must be incorporated into the special education curriculum that facilitate their visual and interactive learning experience. Therefore, this research confirmed the theoretical perspective that the successful integration of technology in learning environments depends on a number of contextual elements, including curriculum alignment, institutional readiness, and user training, highlighting the need for a comprehensive approach to technology adoption.

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References

[1] Lederberg, A. R., Schick, B., & Spencer, P. E. (2013). Language and literacy development of deaf and hard-of-hearing children: successes and challenges. *Developmental psychology*, *49*(1), 15. https://psycnet.apa.org/doi/10.1037/a0029558

[2] Qi, S., & Mitchell, R. E. (2012). Large-scale academic achievement testing of deaf and hard-of-hearing students: Past, present, and future. *Journal of deaf studies and deaf education*, *17*(1), 1-18. https://doi.org/10.1093/deafed/enr028

[3] Marschark, M., & Knoors, H. (2012). Educating deaf children: Language, cognition, and learning. *Deafness & education international*, *14*(3), 136-160. https://doi.org/10.1179/1557069X12Y.0000000010

[4] Toofaninejad, E., Zaraii Zavaraki, E., Dawson, S., Poquet, O., & Sharifi Daramadi, P. (2017). Social media use for deaf and hard of hearing students in educational settings: a systematic review of literature. *Deafness & education international*, *19*(3-4), 144-161. https://doi.org/10.1080/14643154.2017.1411874

[5] Pandey, U., Kumar, V., Kaushik, S., & Sharma, A. (2023). Breaking Barriers: Sign Language-to-Text Transformation in the Digital Era. International Conference on Soft Computing: Theories and Applications, https://doi.org/10.1007/978-981-97-2089-7_33

[6] Banda, N. J. (2024). *Pedagogic strategies teachers use to teach reading in english to grade three deaf learners at selected special needs schools in Lusaka district* The University of Zambia]. https://dspace.unza.zm/handle/123456789/8863

[7] Coy, A., Mohammed, P. S., & Skerrit, P. (2024). Inclusive Deaf Education Enabled by Artificial Intelligence: The Path to a Solution. *International Journal of Artificial Intelligence in Education*, 1-39. https://doi.org/10.1007/s40593-024-00419-9

[8] Fernandes, N., Leite Junior, A. J. M., Marçal, E., & Viana, W. (2024). Augmented reality in education for people who are deaf or hard of hearing: a systematic literature review. *Universal access in the information society*, *23*(3), 1483-1502. https://doi.org/10.1007/s10209-023-00994-z

[9] Lastrucci, A., Wandael, Y., Barra, A., Ricci, R., Maccioni, G., Pirrera, A., & Giansanti, D. (2024). Exploring Augmented Reality Integration in Diagnostic Imaging: Myth or Reality? *Diagnostics*, *14*(13), 1333. https://doi.org/10.3390/diagnostics14131333

[10] Ioannou, A., & Constantinou, V. (2018). Augmented reality supporting deaf students in mainstream schools: Two case studies of practical utility of the technology. Interactive Mobile Communication Technologies and Learning: Proceedings of the 11th IMCL Conference, https://doi.org/10.1007/978-3-319-75175-7_39

[11] Ridha, A. M., & Shehieb, W. (2021). Assistive technology for hearing-impaired and deaf students utilizing augmented reality. 2021 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), https://doi.org/10.1109/CCECE53047.2021.9569193

[12] Zainuddin, N. M. M., Zaman, H. B., & Ahmad, A. (2010). A participatory design in developing prototype an augmented reality book for deaf students. 2010 Second International Conference on Computer Research and Development, https://doi.org/10.1109/ICCRD.2010.55

[13] Mu'alamah, N. N., & Ubaidah, N. (2025). Analysis of mathematical literacy through pull out photo math box based on augmented reality technology in deaf students. *Union: Jurnal Ilmiah Pendidikan Matematika*, *13*(1), 213-239. https://doi.org/10.30738/union.v13i1.19164

[14] Zhang, J., Zhu, R., Li, T., & Yi, C. (2024). Breaking Barriers: Enhancing Learning Outcomes for

Deaf and Hard of Hearing Students through Augmented Reality Captioning. https://aisel.aisnet.org/icis2024/humtechinter/humtechinter/24

[15] Angco, R. J. N., & Angco, L. B. (2024). A Meta-Synthesis of Effective Practices and Outcomes in the Use of Manipulatives for Teaching Mathematics. *Human Behavior, Development & Society*, *25*(2). https://doi.org/10.62370/hbds.v25i2.274848

[16] Bertrand, M. G., Sezer, H. B., & Namukasa, I. K. (2024). Exploring AR and VR Tools in Mathematics Education through Culturally Responsive Pedagogies. *Digital Experiences in Mathematics Education*, *10*(3), 462-486. https://doi.org/10.1007/s40751-024-00152-x

[17] Cascales Martínez, A., Martínez Segura, M. J., Pérez López, D., & Contero, M. (2016). Using an augmented reality enhanced tabletop system to promote learning of mathematics: A case study with students with special educational needs. https://doi.org/10.12973/eurasia.2017.00621a

[18] Özkubat, U., Sanır, H., Özçakır, B., & İslim, Ö. F. (2022). Teaching mathematics, science and reading skills to students with special needs: A review of augmented reality studies. *Journal of Learning and Teaching in Digital Age*, *7*(2), 141-150. https://doi.org/10.53850/joltida.1001800

[19] Zhang, Y., Feijoo-Garcia, M. A., Gu, Y., Popescu, V., Benes, B., & Magana, A. J. (2024). Virtual and augmented reality in Science, Technology, Engineering, and Mathematics (STEM) education: an Umbrella Review. *Information*, *15*(9), 515. https://doi.org/10.3390/info15090515

[20] Bhagat, K. K., Yang, F.-Y., Cheng, C.-H., Zhang, Y., & Liou, W.-K. (2021). Tracking the process and motivation of math learning with augmented reality. *Educational technology research and development*, *69*(6), 3153-3178. https://doi.org/10.1007/s11423-021-10066-9

[21] Bujak, K. R., Radu, I., Catrambone, R., MacIntyre, B., Zheng, R., & Golubski, G. (2013). A psychological perspective on augmented reality in the mathematics classroom. *Computers & Education*, *68*, 536-544. https://doi.org/10.1016/j.compedu.2013.02.017

[22] Chen, P., Liu, X., Cheng, W., & Huang, R. (2017). A review of using Augmented Reality in Education from 2011 to 2016. *Innovations in smart learning*, 13-18. https://doi.org/10.1007/978-981-10-2419-1_2

[23] Lee, K. (2012). Augmented reality in education and training. *TechTrends*, *56*, 13-21. https://doi.org/10.1007/s11528-012-0559-3

[24] Sarnita, F., Suma, K., Tika, I., & Candiasa, I. (2024). Analysis of Needs for Interactive Multimedia Development to Improve Literacy and Numeration of Special Needs Students. Conference Proceedings of International Conference on Teaching, Education and Learning (TEL), https://doi.org/10.32789/edcon.2024.3103

[25] Anshori, H., & Novianingsih, K. (2021). The development of mathematics teaching materials integrating by Augmented Reality Software and Android for deaf students. Journal of Physics: Conference Series, https://doi.org/10.1088/1742-6596/1882/1/012043

[26] LiantoBuliali, J. (2021). Innovative learning model with augmented reality technology for deaf students. *Ilkogretim Online*, *20*(1). https://ilkogretim-online.org/index.php/pub

[27] de Oliveira, F. C., Toledo, W. E., Bissaco, M. A. S., & da Silva, R. R. (2022). SpaceGeo_AR: augmented reality application for teaching and learning spatial geometry by deaf and non-deaf students. *Research, Society and Development*, *11*(7), e23211729656-e23211729656. https://doi.org/10.1111/j.1467-8624.2004.00757.x

[28] Suarsana, I. M. (2021). Developing interactive digital mathematics book with multi representation approach for deaf students. *International Journal of Emerging Technologies in Learning (Online)*, *16*(13), 128. https://doi.org/10.3991/ijet.v16i13.22459

[29] Yurmalia, D., & Hasanah, A. (2022). Visualization of deaf and hard hearing students in learning mathematics: A literature review. AIP Conference Proceedings, https://doi.org/10.1063/5.0129951

[30] Izaguirre, E. D. P., Abásolo, M. J., & Collazos, C. A. (2021). Educational methodologies for hearing impaired children supported by mobile technology and extended reality: systematic analysis of literature. *IEEE Revista Iberoamericana de Tecnologias del Aprendizaje*, *16*(4), 410-418. https://doi.org/10.1109/RITA.2021.3135202

[31] Imashev, A., Kydyrbekova, A., Oralbayeva, N., Kenzhekhan, A., & Sandygulova, A. (2024). Learning sign language with mixed reality applications-the exploratory case study with deaf students. *Education and information technologies*, *29*(13), 17261-17292. https://doi.org/10.1007/s10639-024-12525-1

[32] Nebytova, L. A., Katrenko, M. V., Savin, D. I., & Zhuravleva, Y. I. (2021). Augmented reality in the training process of children with hearing disorders. CEUR Workshop Proceedings, https://ceur-ws.org/Vol-2834/Paper28.pdf

[33] Luna, S. M., Xu, J., Papangelis, K., Tigwell, G. W., LaLone, N., Saker, M., Chamberlain, A., Laato, S., Dunham, J., & Wang, Y. (2024). Communication, Collaboration, and Coordination in a Co-located Shared Augmented Reality Game: Perspectives From Deaf and Hard of Hearing People. Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems, https://doi.org/10.1145/3613904.3642953

[34] Korkmaz, E., & Morali, H. S. (2022). A meta-synthesis of studies on the use of augmented reality in mathematics education. *International Electronic Journal of Mathematics Education*, *17*(4), em0701. https://doi.org/10.29333/iejme/12269

[35] Mualamah, N. N., Lestari, F. P., Anggreini, C. A., Yasinta, E., Widiyawati, W., & Ubaidah, N. (2024). Pull Out Photo Box with AR Technology in Supporting Mathematics Literacy in Deaf Crew Members. *Kontinu: Jurnal Penelitian Didaktik Matematika*, *8*(2), 135-151. http://dx.doi.org/10.30659/kontinu.8.2.135-151

[36] Marwah, R., Thakur, J. S., & Tanwar, P. (2024). Augmented Reality Assistive Technologies for Disabled Individuals. *arXiv preprint arXiv:2409.02053*. https://doi.org/10.48550/arXiv.2409.02053

[37] Aljedaani, W., Krasniqi, R., Aljedaani, S., Mkaouer, M. W., Ludi, S., & Al-Raddah, K. (2023). If online learning works for you, what about deaf students? Emerging challenges of online learning for deaf and hearing-impaired students during COVID-19: a literature review. *Universal access in the information society*, *22*(3), 1027-1046. https://doi.org/10.1007/s10209-022-00897-5

[38] Dudley, J., Yin, L., Garaj, V., & Kristensson, P. O. (2023). Inclusive Immersion: a review of efforts to improve accessibility in virtual reality, augmented reality and the metaverse. *Virtual Reality*, *27*(4), 2989-3020. https://doi.org/10.1007/s10055-023-00850-8

[39] İbili, E., Çat, M., Resnyansky, D., Şahin, S., & Billinghurst, M. (2020). An assessment of geometry teaching supported with augmented reality teaching materials to enhance students' 3D geometry thinking skills. *International Journal of Mathematical Education in Science and Technology*, *51*(2), 224-246. https://doi.org/10.1080/0020739X.2019.1583382

[40] Luna, S. M., Xu, J., Tigwell, G. W., LaLone, N., Saker, M., Chamberlain, A., Schwartz, D. I., & Papangelis, K. (2025). Exploring Deaf And Hard of Hearing Peoples' Perspectives On Tasks In Augmented Reality: Interacting With 3D Objects And Instructional Comprehension. http://dx.doi.org/10.1145/3706598.3713678

[41] Amores-Valencia, A., Burgos, D., & Branch-Bedoya, J. W. (2022). Influence of motivation and academic performance in the use of Augmented Reality in education. A systematic review.

Frontiers in psychology, *13*, 1011409. https://doi.org/10.3389/fpsyg.2022.1011409

[42] SARNOU, P. P. D. H. (2024). *Enhancing Communication among Deaf and Hard of Hearing (DHH) Individuals with Language Learning Apps: Case of 15 DHH in Mostaganem* Ministry of Higher Education]. http://e-biblio.univ-mosta.dz/bitstream/handle/123456789/28360/Full-Dissertation%20-Cherifa%20Benslimane%20(1).pdf?sequence=1

[43] AlNajdi, S. M. (2022). The effectiveness of using augmented reality (AR) to enhance student performance: using quick response (QR) codes in student textbooks in the Saudi education system. *Educational technology research and development*, *70*(3), 1105-1124. https://doi.org/10.1007/s11423-022-10100-4

[44] Alanazi, M. (2020). The Experiences of Deaf and Hard of Hearing Students and Specialist Teachers in Mainstream Schools in Saudi Arabia. https://pearl.plymouth.ac.uk/pioe-theses/11

[45] Intarapreecha, N., & Sangsawang, T. (2023). Incorporating augmented reality to enhance learning for students with learning disabilities: a focus on spatial orientation in physical. *Journal of Applied Data Sciences*, *4*(3), 245-253. https://doi.org/10.47738/jads.v4i3.126

[46] Wong, J. Y., Azam, A. B., Cao, Q., Huang, L., Xie, Y., Winkler, I., & Cai, Y. (2024). Evaluations of virtual and augmented reality technology-enhanced learning for higher education. *Electronics*, *13*(8), 1549. https://doi.org/10.3390/electronics13081549

[47] Shaaban, T. S., & Mohamed, A. M. (2024). Exploring the effectiveness of augmented reality technology on reading comprehension skills among early childhood pupils with learning disabilities. *Journal of Computers in Education*, *11*(2), 423-444. https://doi.org/10.1007/s40692-023-00269-9

[48] Wang, L., Zhang, Q., & Sun, D. (2025). Exploring the impact of an augmented reality-integrated mathematics curriculum on students' spatial skills in elementary school. *International Journal of Science and Mathematics Education*, *23*(2), 387-414. https://doi.org/10.1007/s10763-024-10473-3

[49] Yanuarto, W. N., Suanto, E., & Isnawan, M. G. (2024). Augmented reality for mathematics learning: A study for enhancing mathematical comprehension in high school students. *JTAM (Jurnal Teori dan Aplikasi Matematika)*, *8*(3), 910-923. https://journal.ummat.ac.id/index.php/jtam/article/view/22778

[50] Nadzeri, M. B., Musa, M., & Ismail, I. M. (2024). The Effects of Augmented Reality Geometry Learning Applications on Spatial Visualization Ability for Lower Primary School Pupils. *International Journal of Interactive Mobile Technologies*, *18*(16). https://doi.org/10.3991/ijim.v18i16.47079

[51] Nasir, N., Ibrahim, A. B., Asmadi, M. S., Pandyan, M., Jie, L. L., & Hussin, M. S. Z. (2023). Augmented reality learning in mathematics education: systematic literature review. *International Journal of Education, Science, Technology, and Engineering (IJESTE)*, *6*(2), 47-54. https://doi.org/10.36079/lamintang.ijeste-0602.581

[52] Andriyani, A., Buliali, J. L., & Pramudya, Y. (2022). Development of Augmented Reality Media Based On Cybernetic Learning Theory to Stimulate Spatial Abilities. *Journal of ICSAR*, *6*(2), 151. http://dx.doi.org/10.17977/um005v6i22022p151

[53] Liu, P. H. E., & Tsai, M. K. (2013). Using augmented-reality-based mobile learning material in EFL English composition: An exploratory case study. *British journal of educational technology*, *44*(1), E1-E4. https://doi.org/10.1111/j.1467-8535.2012.01302.x

[54] Afrashtehfar, K. I., Yang, J.-W., Al-Sammarraie, A., Chen, H., & Saeed, M. H. (2023). Pre-clinical undergraduate students' perspectives on the adoption of virtual and augmented reality to their dental learning experience: A one-group pre-and post-test design protocol.

F1000Research, *10*, 473. https://doi.org/10.12688/f1000research.53059.2

[55] Budiman, R. (2016). Developing learning media based on augmented reality (AR) to improve learning motivation. *Journal of Education, Teaching and Learning*, *1*(2), 89-94. https://journal.stkipsingkawang.ac.id/index.php/JETL/article/view/45

[56] Debnath, T. (2021). Investigating the Effectiveness of an Augmented Reality Game to Enhance the Mathematics Learning Experience of Dyscalculic. https://doi.org/10.21203/rs.3.rs-996267/v1

[57] Chao, W.-H., & Chang, R.-C. (2018). Using augmented reality to enhance and engage students in learning mathematics. *Advances in Social Sciences Research Journal*, *5*(12), 455-464. https://doi.org/10.14738/assrj.512.5900.

[58] Nunes, T. (2020). Deaf children, special needs, and mathematics learning. *Encyclopedia of Mathematics Education*, 181-183. https://doi.org/10.1007/978-3-030-15789-0_42

[59] İslim, Ö. F., Namlı, Ş., Sevim, N., Özçakır, B., & Lavicza, Z. (2024). Augmented Reality in Mathematics Education: A Systematic Review. *Participatory Educational Research*, *11*(4), 115-139. https://doi.org/10.17275/per.24.52.11.4

[60] Lah, N. H. C., Senu, M., Jumaat, N. F., Phon, D. N. E., Hashim, S., & Zulkifli, N. N. (2024). Mobile augmented reality in learning chemistry subject: an evaluation of science exploration. *International Journal of Evaluation and Research in Education*, *13*(2), 1007-1020. https://doi.org/10.11591/ijere.v13i2.25198