Education Tech Research Dev
https://doi.org/10.1007/s11423-025-10551-5

DEVELOPMENT ARTICLE

Effects of immersive augmented reality learning environment for hearing-impaired students' reading achievement, perceptions, and behaviors

Xiao-Fan Lin[1,2] · **Xiyu Huang**[3] · **Xiaoqing Xian**[3] · **Jiahao Miao**[3] · **Wei Zhou**[3] · **Yilin Zheng**[3] · **Wenyi Li**[3]

Received: 27 October 2023 / Accepted: 27 June 2025

Abstract

The reading ability of hearing-impaired students is essential for their participation in mainstream society. However, previous studies have shown that they may encounter obstacles due to a lack of interest or limitations in reading communication systems. Augmented reality (AR) has been noted to provide immersive learning environments, collaborative assistance, and in-time resources for improving reading experience and motivation. While previous studies have developed mobile reading environments tailored for hearing-impaired students, the incorporation of pedagogical approaches within immersive AR reading environments remains unexplored. Accordingly, this study investigated the effects of immersive AR environments on hearing-impaired students' reading with a quasi-experiment. Sixty-five hearing-impaired students' reading achievement, perceptions, and behaviours were analysed with one-way analysis of covariance and lag sequential analysis. The result indicated that the immersive AR learning environment incorporating the DEEP reading strategy (i.e., Developing self-regulated reading, Experimental exploration, Express and creative construction, and Pluralism) improved hearing-impaired students' reading achievement, perceptions, and behaviours. Students with the immersive AR reading strategy exhibited more interactive-oriented behaviours and high levels of cognitive attainment (e.g., experiential exploration, creative construction, and problem-solving). This study contributed to existing hearing-impaired teaching practices by revealing what essential behaviour teachers should consider and how to design an immersive AR learning environment.

Keywords Augmented reality (AR) · Hearing Impairment · Students · Reading · Behaviour · Educational technology

Introduction

Reading ability is a skill that is necessary for hearing-impaired students to participate in mainstream society as ordinary students do (Escudeiro et al., 2022). Accordingly, research evidence has emphasized the need to promote hearing-impaired students' reading achievement (Luangrungruang & Kokaew, 2022; Soogund & Joseph, 2019), interacting with them

Extended author information available on the last page of the article by providing interactive online resources in online inclusive education courses (Hsieh, 2023), and optimise their behaviours when reading with an interactive storybook to acquire knowledge (Trussell et al., 2017). However, without appropriate media, hearing-impaired students may have difficulties integrating suitable learning resources in their reading and writing since most academic content is only written and printed (Luangrungruang & Kokaew, 2022). Despite recognizing the benefits of interactive mobile devices for children's literacy skills, including vocabulary learning, story comprehension and reading engagement (Zhou & Yadav, 2017), few researchers have integrated appropriate strategies into technology-enhanced immersive reading environments. Hence, during the reading process, hearing-impaired students are likely to have a negative attitude toward using technology without learning assistance (Seale et al., 2021). There is thus an urgent need to develop and apply suitable technologies (i.e., incorporate suitable pedagogy into emerging technologies) to take positive advantage of using assistive technologies to ensure that hearing-impaired students obtain the same learning opportunities as hearing students (Escudeiro et al., 2022).

Augmented reality (AR) is considered a suitable technology for promoting reading interest and motivation among deaf and hard of hearing individuals (Oral & Kalkan, 2024). It provides an immersive real and virtual integrated reading environment, collaborative learning assistance, interactive reading contexts, and timely resources to enhance the reading experience and reduce learning barriers caused by hearing impairment (Chen & Chao, 2008; Ebadi & Ashrafabadi, 2022; Na & Yun, 2024). The importance of using suitable assistive technology has been noted to provide visual supports and interactive instruction for cultivating hearing-impaired students with reading achievement, interest, and academic outcomes in inclusive education (Strnadová et al., 2023). AR possibly aids hearing-impaired students by employing visual compensation techniques to enhance their reading abilities, ultimately bridging the gap between them and their hearing peers, improving literacy and competence, and addressing communication barriers (Herrera et al., 2021). Furthermore, the integration of effective teaching strategies and resources is crucial for addressing the information requirements of students with hearing impairments (Onuigbo et al., 2020). The utilization of digital resources specifically designed for students with impairments, such as hearing-impaired students, is widely acknowledged as a highly effective pedagogical approach, nevertheless, it is imperative to seamlessly integrate these teaching resources with other instructional strategies at both the classroom and virtual levels (Cotán et al., 2021). Specifically, there is a lack of studies exploring how to incorporate suitable pedagogy into an immersive AR learning environment (Herrera et al., 2021; Hwang et al., 2018). Accordingly, this study established an integrated pedagogy immersive AR learning environment for hearing-impaired students and investigated its effects on their reading achievement, perceptions, and behaviours.

Literature review

Hearing-impaired students' reading

Reading is defined by Progress in International Reading Literacy Study as a constructive and interactive process in which readers comprehend and use written language for social purposes (Mullis et al., 2016) and could be deemed a complex process of "knowing" and "learning" (National Assessment Governing Board U. S. Department of Education, 2019).

Reading comprehension lessons emphasize the teacher's guidance and enlightenment. Teachers cannot replace students' reading experiences and thinking with mere patterned interpretations or communication. Instead, they should encourage students to read creatively based on understanding, develop higher-order thinking, and improve the quality of reading (Assaly & Jabarin, 2021; Yousef, 2021). Thus, reading for hearing-impaired students should be guided to activities with understanding and creation as the core purpose and interactive dialogue as the existing form in this study.

In this study, hearing-impaired students are defined as a group with the following characteristics: (a) moderate to severe sensorineural hearing loss bilaterally; (b) hearing aids fitted in both ears and used regularly; (c) hearing aids used for at least six months (Elawady et al., 2019). For hearing-impaired students, reading is not only an important way they get information but also their necessary ability to return to the mainstream of society (Escudeiro et al., 2022). The researchers (e.g., Krasavina et al., 2019) have confirmed the unique characteristics of information perceptions of deaf and hearing-impaired students in dealing with reading materials (e.g., paper and interactive whiteboard). Based on these findings, they proposed several suggestions to cultivate normal students' competencies to cooperate with hearing-impaired students in an inclusive education system. Trussell et al. (2017) pointed out an effective vocabulary teaching strategy with interactive storybook reading, which developed learning guidance for deaf and hard-of-hearing children to narrow the difference with their hearing peers. Escudeiro et al. (2022) provided an immersive gamified learning environment to satisfy their high-level requirements and to allow them to enjoy the same learning opportunities as their hearing peers. In their comprehensive review of scientific findings concerning assistive technology from 2009 to 2020, Fernández-Batanero et al. (2022) discovered that assistive technology has emerged as an accessible and inclusive tool that effectively addresses the educational requirements of students with disabilities, including those who are hearing-impaired, within the context of the learning process. However, these studies only assisted students in reaching the level of reading comprehension comparable to their peers (Aldeeb et al., 2024). Few studies have discussed how to guide hearing-impaired students into activities involving deeper cognitive development, such as self-regulated reading, individualised expression, cognitive load, and reprocessing comprehended texts to form creative works after reading, which was the main focus of the present study.

AR learning environment

AR learning environment refers to the real learning environment enhanced by artificial vision technology where the integration of both real and virtual information brings contextual experience for users (Wojciechowski & Cellary, 2013). Existing studies have proven the significant effect of AR learning environment on students' reading. For instance, integrating AR-based resources creates an interactive environment and gives learners contextual knowledge of the content (Chen & Mokmin, 2024). Lai et al. (2019) developed a multimedia system with an AR approach which presented understandable materials that could help students evoke relevance between the concepts and consequently reduce the dilemma of textbook reading for students. Concerning hearing-impaired students, previous studies have indicated the positive role of the immersive technology environment in helping their learning process (Han et al., 2017). Since hearing-impaired students have a more developed sense of visual attention to compensate for their lack of hearing, visual interaction based on immersive technology (e.g., AR) has the potential to support hearing-impaired students' reading (Herrera et al., 2021). By extending the boundaries of reality through audio-visual aids, AR empowers hearing-impaired learners' to comprehend textual information via interactive audiovisual media on mobile devices, thereby equipping them with the adaptability to diverse environmental settings, which has received significant attention in research and discussions (Del Pezo Izaguirre et al., 2021). Three advantages of using AR in facilitating interactive reading may shed light on possible contributions of AR to support hearing-impaired students' reading. First, using AR could create multi-dimensional and immersive experiences for interaction. It allows hearing-impaired students to perform actions that cannot be done naturally in the real world, consequently increasing their satisfaction and stimulating active participation for students to proceed to read (Penenory et al., 2018). Second, behavioural data recorded by the AR system can be essential evidence for instructors to scaffold and adjust students' reading (Wojciechowski & Cellary, 2013). Third, the application of AR stimulates the interest of hearing-impaired students during the reading process (Luangrungruang & Kokaew, 2018), thus providing them with more opportunities for creativity and expression.

Hidi and Renninger's Four-Phase Model of Interest Development highlights how motivation drives the transition from situational interest to maintained and individual interest, which is crucial for deep learning. Interest and motivation are closely connected, with interest acting as a distinct type of motivation. It combines cognitive and emotional elements, encourages intrinsic engagement, and develops through interactions between individuals and their environment. This process helps sustain effort and supports meaningful learning over time. Interest and motivation are closely intertwined, as interest combines affective and cognitive engagement to sustain effort and persistence in learning tasks (Hidi & Renninger, 2006).

Motivation is critical for engaging hearing-impaired students in deep cognitive learning processes. Hearing-impaired students often face unique challenges requiring tailored support to sustain their learning motivation, as it directly influences their ability to engage with and persist in performing learning tasks (Han et al., 2017). Individual interest, as a form of developed motivation, emerges when learners maintain consistent engagement over time and show a deeper connection to the learning material. This interest is reflected in specific behaviours such as self-initiated exploration, persistence in challenging tasks, deeper cognitive processing, and relentless attempts to overcome difficulties (Chen et al., 2024a, 2024b; Hidi et al., 2004; Lin et al., 2023). By integrating behavioural analysis, there is an opportunity to bridge the gap between theory and practice, providing concrete evidence of how AR technology aligns with the affective and cognitive processes necessary for motivation development.

However, although the use of AR affords advantages in improving students' reading performance, the difficulties of in-depth AR-based pedagogical design do not appear to be well grounded. Researchers have argued that issues related to the burden of reading support should be considered more carefully in an immersive AR environment (Ibanez et al., 2020). For example, the excessive level of interactivity in an immersive AR environment may disturb students' reading concentration (Wang et al., 2019). Without appropriate designs for addressing the issues related to reading difficulties, simply introducing AR applications into the reading environment may cause unfavourable results.

It can be concluded that AR technology has the potential to address communication gaps and enhance learning and hearing skills for hearing-impaired students. However, it remains to be seen how to integrate AR technology with teaching scaffoldings and approaches in an immersive AR learning environment (Herrera et al., 2021). Accordingly, the current research is one of the pioneering studies to summarise the above literature regarding AR learning environments to develop a compelling deep reading with the immersive AR learning environment for hearing-impaired students' reading. Based on the previous studies, the immersive AR learning environment could be a similar combination of suitable scaffoldings and a reading environment. The immersive AR learning environment consists of four scaffoldings: motivation stimulus, experience development, interactive self-regulated reading, and in-depth reading communication and collaboration as a cycle to address the challenges of conventional hearing-impaired students' reading.

The focus of the present study

To promote their reading from a self-regulated to creative perspective, this study further proposed a modified DEEP reading with the immersive AR learning environment for hearing-impaired students' reading by replacing the "in-depth reading communication and collaboration" scaffoldings with "express and creative construction" and "pluralism". In addition, since the role of combining self-regulated learning and mobile AR has been emphasized by the previous study (e.g., Huang et al., 2016) to help readers communicate asynchronously to create an online sharing community, obtain books efficiently, address the obstacle of learning domain unawareness, this study incorporates self-regulated reading as the first step for hearing-impaired students to experience the immersive AR learning environment. With the modified scaffoldings immersive AR learning environment, the students collaborated to build in-depth knowledge with an immersive experience.

This study combined suitable scaffoldings and immersive AR reading environments, which were divided into four stages: Developing self-regulated reading, Experiential exploration, Express and creative construction, and Pluralism (i.e., the DEEP reading strategy). Thus, this study investigated hearing-impaired students' reading achievement, perceptions, and behaviours in the immersive AR learning environment. First, for educational research, what learning outcomes hearing-impaired students achieve was an essential topic that researchers were concerned with (Luangrungruang & Kokaew, 2022). Learning achievements could be considered as a representative form of cognitive attainment in an immersive AR environment, that is, what knowledge learners obtain. Second, recording and analysing hearing-impaired students' reading behaviours with immersive AR materials is valuable for understanding the in-depth reading activities of students with special needs. To date, the latent sequential analysis method of exploring hearing-impaired students' behaviours is still in its infancy and should be worth investigating in this field. Third, a crucial yet not fully explored characteristic of students' reading in an immersive AR environment might be students' perceptions. The hearing-impaired students' perceptions can demonstrate their attention, memory, and cognitive situation in reading digital materials (Krasavina et al., 2019). However, among AR-based reading research, a limited number of studies (Cheng, 2019; Lin et al., 2023) have mainly explored the relevant issues. There is a dearth of empirical research concerning how to incorporate suitable pedagogy into immersive AR learning environments for hearing-impaired students. Therefore, this study intended to minimise the literature gap by identifying hearing-impaired students' perceptions and behavioural patterns of reading in an immersive AR environment. Hearing-impaired students' perceptions of their motivation and cognitive load for reading were explored. Several research questions were proposed as follows:

(1) To what extent may reading in an immersive AR environment approach improve hearing-impaired students' reading achievement and reading creation performance compared to conventional reading with AR-based books?
(2) What are the differences in hearing-impaired students' perceptions (i.e., reading motivation and cognitive load) between reading with an immersive AR environment approach and conventional reading with AR-based books?
(3) What are the differences in behavioural patterns of hearing-impaired students between reading with an immersive AR environment and conventional reading with AR-based books?

The system and procedure of this study

The development of the AR-based reading system

To facilitate the reading achievement and cognitive development of hearing-impaired students, the current study developed an AR-based reading system. Figure 1 shows the system's structure, which includes the AR mechanism, the mobile reading guidance and feedback mechanism, and several databases. The AR mechanism and the mobile reading guidance and feedback mechanism each comprise three functions as shown in Fig. 1.

To mitigate the challenges faced by hearing-impaired students in accessing and engaging with reading materials, we have modified the deep cognitive reading strategy integrating the immersive AR learning environment. Specifically, the AR mechanism could narrow the hearing input gap and foster a more inclusive deep cognitive reading environment with

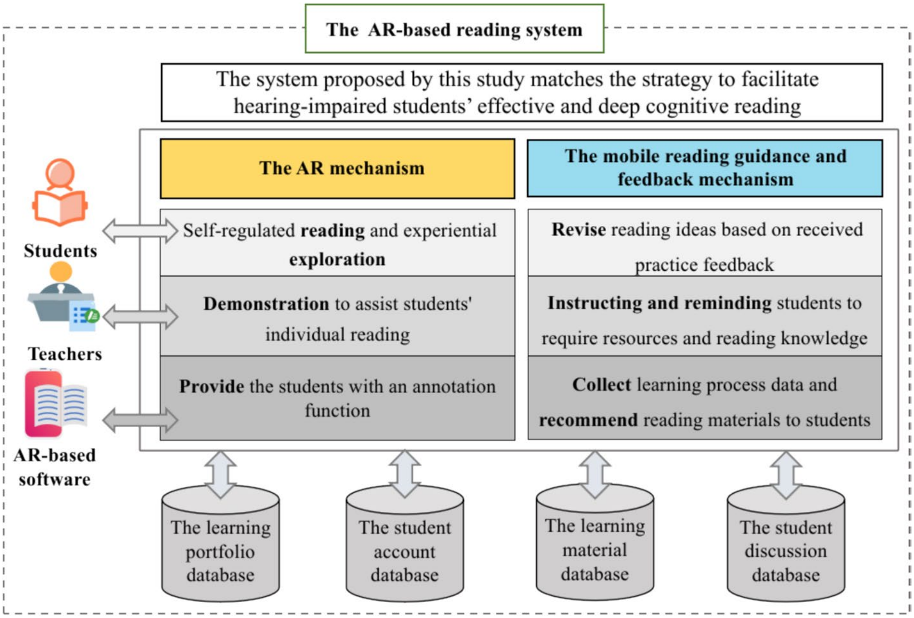


Fig. 1 Structure of the immersive AR-based reading system

the following three functions: (1) The experimental group students immerse themselves in a reading learning environment crafted by the AR-based system, enabling them to engage in self-paced and reflective reading practices. This function matches the strategy of fostering autonomy and critical thinking, which is essential for deep reading; (2) The teacher utilizes AR-based books to assist students in the control group with their individual reading tasks, ensuring that all students, regardless of their hearing abilities, receive personalized instruction. This function aligns with the strategy of differentiated instruction, which is tailored to meet the unique needs of each student; (3) The AR-based software equips students with a robust annotation tool, allowing them to mark up text, images, audio, and video content. This not only supports their active engagement with the material, but also facilitates a deeper understanding by enabling them to connect multiple forms of media. This function corresponds with the strategy of multimedia learning, which leverages various sensory channels to enhance comprehension.

To better ensure the integrating effects of deep cognitive reading scaffoldings and immersive AR reading environments, the mobile reading guidance and feedback mechanism also has three functions: (1) When students receive practice feedback, they can revise and refine their reading comprehension, thus enhancing their deep learning experience. This function aligns with the strategy of iterative learning and reflection, fostering a deeper understanding of the text; (2) The teacher monitors students' progress and provides instructions and reminders through the AR system, ensuring the students access the necessary resources and reading knowledge. This function supports the strategy of differentiated instruction, catering to the unique learning needs of hearing-impaired students; (3) The AR-based software collects learning process data and recommends personalized AR-based reading materials to students, further enhancing their reading engagement and deepening their comprehension. By leveraging these functions, the system aims to narrow the gap in reading input between hearing-impaired students and their hearing peers, ultimately facilitating a more inclusive and equitable learning environment.

The usage of strategy to facilitate hearing-impaired students' reading with AR-based resources

To explore the hearing-impaired students' reading achievement, perceptions, and behaviours in the immersive AR learning environment, this study was based on a quasi-experimental design that consisted of the experimental and the control group. The experimental group adopted an immersive AR reading strategy based on the immersive AR environment and included four stages: Developing self-regulated reading, Experiential exploration, Express and creative construction, and Pluralism. The control group adopted conventional reading with an AR-based books strategy, which would pass through the following four stages: Concepts cognition, Difficult knowledge explanation, Exercises and consolidation, and Practice and application.

In the experimental group, hearing-impaired students engaged in immersive reading activities using the proposed strategy, which was designed to foster deep cognitive engagement and creative learning. As illustrated in Fig. 2, students began by forming a collaborative reading community within the immersive AR environment. This initial phase supported shallow cognitive processing, enabling students to acquire basic information and build context for the reading material.

Following this, the teacher introduced AR manipulation guidelines and scaffolded reading tasks, providing structured opportunities for the students to interact with the immersive

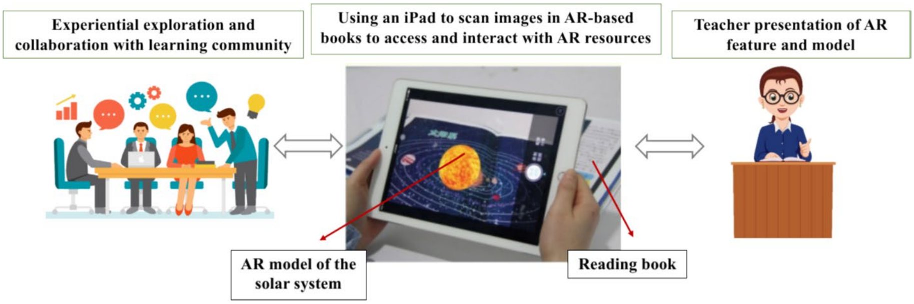


Fig. 2 Reading strategies for hearing-impaired students

AR resources and pose individualized questions. By engaging with immersive AR models and collaborating within the reading community, students transitioned to more complex cognitive processes, including analysing the information and applying it to problem-solving scenarios.

Figure 3 shows that students utilized their insights to produce creative works. The work images illustrate that students in the experimental group demonstrated more diverse and elaborate forms of visual presentation and representation of the reading materials in their creative endeavours compared to those in the control group. These activities allowed students to engage in expressive and creative construction, demonstrating their ability to synthesize and reimagine the reading material. This exemplifies how the refined reading input strategies within the AR-based reading system fostered deep learning among hearing-impaired students.

Finally, throughout the immersive learning process, students participated in multiple assessments aimed at deepening their understanding and fostering inclusive perspectives on the reading text. The integration of immersive AR technology in this strategy enabled hearing-impaired students to achieve a richer, more inclusive reading experience, fostering both cognitive and creative growth.

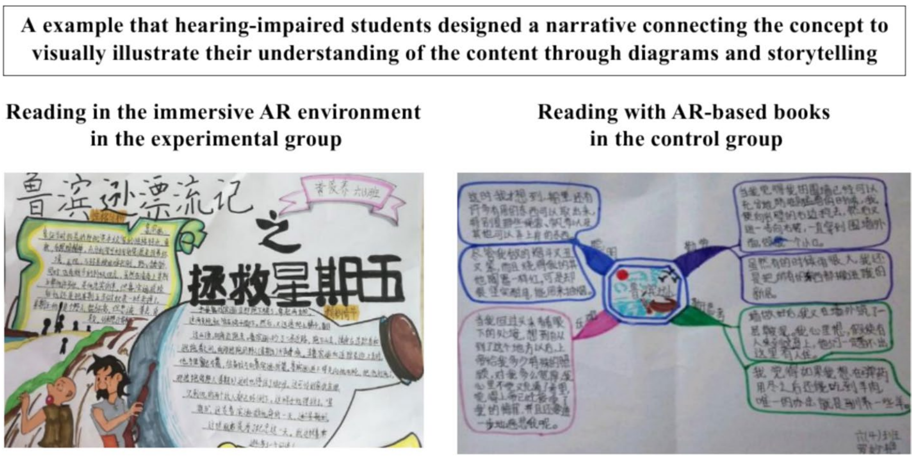


Fig. 3 Creative work of reading

In the control group, the teacher carried out four-stage teaching with the aid of the common media equipment (i.e., PowerPoint courseware, computer, projector, audio, video, etc.) and the coordination of AR teaching resources. Firstly, hearing-impaired students experienced individual reading with AR-based books to cognise new concepts. Secondly, the teacher taught the difficult knowledge and demonstrated the AR reading resources' annotation function for hearing-impaired students to understand and consolidate the knowledge. Then, based on knowledge understanding, hearing-impaired students deepened their understanding of the concepts and formed general conclusions by answering questions. Finally, according to conventional reading instructions steps demonstrated by the teacher, hearing-impaired students were required to reproduce the experimental process by AR to realise the transfer and application of the learned knowledge.

Procedure and the context

Figure 4 shows the experiment procedure, which was conducted for eight weeks. During the first week, students in both groups were required to complete the pre-test and pre-questionnaires to exclude the effect on students' achievement and perception.

The learning activities for the experimental and control groups consisted of four similar interactive stages, and all of the participants were taught by the same teacher. All participants in both groups were arranged in the learning content regarding reading and the same

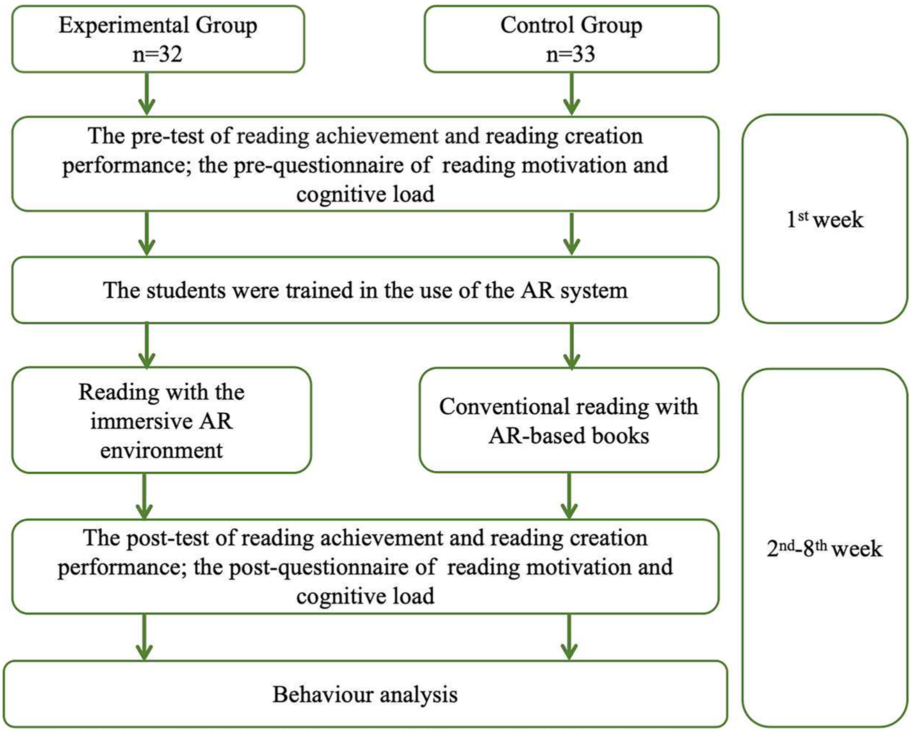


Fig. 4 Experimental procedure

AR-based resources and multi-annotation functions (i.e., recording, text, voice input, photo uploading, etc.).

The difference between the two groups was that the students in the experimental group learned with an immersive AR reading strategy. In contrast, the control group adopted conventional reading with AR-based books. For instance, after the experimental group, students experienced AR-based resources under the teacher's guidance and discussed with their learning community. Unlike the experimental group, the students in the control group did practical exercises after the teacher demonstrated the AR function and only worked in groups to reproduce the experimental procedures during the practice and application stage. Moreover, the experimental group collaborated intensely as teacher-student and student–student learning communities to achieve creative constructions of the reading materials. Though the teacher gave direct answers when students encountered problems in the control group, it is worth noting that students would be guided by the teacher in a similar situation instead.

Method

This study employed a quantitative quasi-experimental design to explore the effects of an immersive AR learning environment on hearing-impaired students' reading achievement, perceptions, and behaviours. A total of 65 hearing-impaired students in sixth grade were divided into experimental and control groups, allowing for comparison of the immersive AR-based reading strategies and conventional AR reading approaches.

Several potential biases and constraints were considered in the design. First, self-reported data gathered through questionnaires are subjective and prone to biases, such as participants selecting more positive responses. This could lead to overestimation of outcomes such as motivation. To address this, the study incorporated behavioural observation via video-recorded analyses, thereby offering objective data on the interactions and engagement of hearing-impaired students' reading process. This approach helps counterbalance biases inherent in the subjectivity of self-reports, and ensures a more comprehensive understanding of the hearing-impaired students' reading. Second, while quasi-experimental designs typically assess the overall effectiveness of an intervention, this study aimed to explore specific periods of the intervention in greater depth. The quasi-experimental design was chosen for its ability to assess the impact of the intervention as a whole, while the behavioural analysis provided detailed insights into the key moments of student engagement. This combination allowed for a more nuanced understanding of the effects of the immersive AR environment on hearing-impaired students. To ensure validity, a triangulation approach was applied (Elliott, 1991). This methodological triangulation enhances confidence in the results by integrating different sources of evidence, enabling a comprehensive and balanced perspective on the effectiveness of the intervention.

Participants

This study explored the hearing-impaired students' reading performances in reading learning by providing students with books with a corresponding AR system, which supported a more informatively contextual experience with multimedia reading materials. A total of 65 sixth grade hearing-impaired students involved in the project from a special primary school in Southern China were randomly selected as the experimental group using the proposed approach. The other was the control group using the conventional reading with AR-based books approach. The experimental group consisted of 32 students (mean age = 11.57), of whom 15 were male and 17 were female. The control group consisted of 33 students (mean age = 11.21), of whom 17 were male and 16 were female. These two groups were taught by the same teacher. To ensure the accuracy of the experimental results, none of the participants had any prior experience using AR technology in reading. The inclusive course was selected because it included a series of multi-subject interdisciplinary (e.g., science, language, mathematics, and art). The curriculum also involved students completing a project that required the students to learn in group activities. In addition, the overall process of students' behaviours was also recorded by video. Students in this study were also required to participate in the learning activities guided by a system with an AR-based reading approach.

Instruments

Reading achievement

The hearing-impaired students' reading achievement was measured by reading tests designed by consulting the teachers in special education with teaching experience of more than ten years. The tests are modified from the Progress in International Reading Literacy Study Digital Reading Test (2016 Edition) conducted by the International Association for the Evaluation of Educational Achievements for primary school students (Mullis et al., 2016). The test mainly includes four dimensions: concentration and retrieval of designated information, direct reasoning, interpretation and integration of ideas and information, evaluation, and criticism of content and text. The reading test consisted of a pre-test and a post-test, each of them contained two matching items (20%), four multiple-choice items (40%), two fill-in-the-blank items (20%), and one short-answer question (20%) with a total score of 100. Sample questions in each test are shown below:

(1) Pre-test sample question: Why does the ten-million-kilometre journey to Mars have to be planned a long time in advance?
(2) Post-test sample question: Why Mars rovers can almost explore Mars like humans?

Reading creation performance

The hearing-impaired students' reading performance was determined by the quality of their creative works. Four aspects of evaluative criteria, namely related to reading goal, correct reading concept, fluency, and genesis, were established to grade the creative products with reference to the scale developed by Liu et al. (2014). Related to reading goals refer to creative work that includes reading goals set by the groups. The correct reading concept means the embedded reading creative works are correct. Fluency represents that the main ideas of creative work are clear and concrete. The Genesis characterises creativity associated with an aggregate of experiences (or memories) and comprises a series of students' original products, performances, ideas, and methods, which could be for any identified need. The overall evaluation criteria for the four aspects is 100 points. Each aspect of the evaluative criteria consisted of 25 points (the lowest score = 1 point; the highest score = 25 points). Students' creative drawings were evaluated by teachers and researchers. The inter-rater reliability kappa was 0.86, suggesting a high agreement between the raters (Cohen, 1960).

Reading motivation

The reading motivation questionnaire was modified based on Guthrie and Klauda's (2014) scale, which includes intrinsic motivation (3 items), perceived value (3 items), and perceived self-efficacy (3 items) subscales, which were modified for further analysis in this study to fit well with the context of AR reading for hearing-impaired students. The refined reading motivation questionnaire was rated by students on a 5-point Likert-type scale (1-strongly disagree, 2-disagree, 3-disagree nor agree, 4-agree, and 5-strongly agree). The Cronbach's alpha reliability of the questionnaire was 0.82. Thus, the questionnaire was sufficiently reliable for assessing students' motivation in reading with AR. The sample items for each scale are as follows:

(1) Intrinsic motivation sample question: It was fun to do the AR-based reading.
(2) Perceived value sample question: I would like to spend my time and effort on reading.
(3) Perceived value sample question: I can give correct answers to most reading questions in reading exercises.

Cognitive load

The questionnaire for assessing hearing-impaired students' cognitive load was administered by adapting the original scale of Chen et al. (2022) and Paas and van Merriënboer (1994). The scale modification for suiting hearing-impaired students retained ten items in two dimensions: mental load and mental effort. The items were rated on a 5-point Likert scale ranging from "strongly disagree" to "strongly agree". The Cronbach's alpha values of mental load and mental effort are 0.81 and 0.85, respectively, indicating acceptable reliability of the scale. The following items explain each dimension of the cognitive load scale in the AR-based reading context:

(1) Mental effort: students' reactions to the instructions of the learning task to complete the reading tasks in immersive AR environments (e.g., I devoted much energy to the AR reading).
(2) Mental load: students' perceived difficulty in reading AR content, learning tasks, and materials to understand new information (e.g., It is difficult for me to be attentive in reading AR materials).

Reading behaviour

Based on an AR learning behavioural coding scheme addressed by previous studies (Lin et al., 2023) and the hearing-impaired students' learning support proposed by Izaguirre et al. (2021) suggestions, this study developed a coding scheme revealing possible behaviours of hearing-impaired students' AR-based reading, as shown in Table 1.

According to Anderson and Krathwohl's (2001) classification of cognitive process, presenting a continuum of increasing cognitive complexity from lower order to higher order level of thinking skills has also been used as a framework to analyse hearing-impaired students' levels of cognitive learning. To contribute to AR-based reading research, in the present study we considered that L1-L5 could be examined as low-level

Table 1 Coding scheme

Code	Behaviour
L1	Read the content of the book himself/herself
L2	Operate the AR elements of the book from the AR system
L3	Answer the tasks in the AR system (i.e., reading test, creative tasks)
L4	Search the Internet for information on the tasks
L5	Take personal annotations on the AR-based book in the AR system
H1	Explore problems according to the reading goals
H2	Read the feedback on the tasks from the AR system
H3	Interact with peers regarding the reading content
H4	Explore problem-solving activities with peers
H5	Give comments for help on others' pages (answers to the tasks, creative works)

cognitive attainment of AR-based reading, while H1-H5 could be considered as high-level cognitive attainment of AR-based reading.

Data analysis

This study employed multiple learning analytics methods to address hearing-impaired students reading achievement, perceptions, and behaviours. The hearing-impaired students' reading achievement test consisted of a pre-test and a post-test, each of them contained two matching items (20%), four multiple-choice items (40%), two fill-in-the-blank items (20%), and one short-answer question (20%) with a total score of 100. The hearing-impaired students' reading performance was evaluated by teachers and researchers. The inter-rater reliability kappa was 0.86, suggesting a high agreement between the raters (Cohen, 1960). The Cronbach's alpha reliability of the reading motivation questionnaire was 0.82. Thus, the questionnaire was sufficiently reliable for assessing students' motivation in reading with AR. The Cronbach's alpha values of mental load and mental effort of the questionnaire for assessing hearing-impaired students' cognitive load were 0.81 and 0.85, respectively, indicating acceptable reliability of the scale. In addition, the items in the cognitive load section employed a reverse scoring method (i.e., when students selected "strongly agree" for these reverse-scored items, they received lower scores, indicating higher cognitive load).

The hearing-impaired students' reading behaviours were collected from digital video camera records. Based on the coding scheme, the behaviour data could be transcribed into the behaviour patterns diagram. Accordingly, two researchers independently coded the observed behaviour according to the coding scheme. They discussed and negotiated some inconsistencies or dilemmas in the coding process. The inter-rater agreement coefficient for the items was 0.84, showing acceptable inter-rater reliability. The lag sequential analysis (LSA) was conducted to understand the changes in students' behaviour during the reading process in the AR context. The statistical significance of behaviour transition was analysed by calculating Z-score (an adjusted residual value) statistics with GSEQ 5.1. Z-scores greater than 1.96 indicated significant behavioural transformation data, which was filtered to obtain the behaviour patterns of students (Bakeman & Gottman, 1997).

Table 2 The ANCOVA result of reading achievement

Group	*N*	Mean	*SD*	Adjusted *SD*	Adjusted mean	*F*	η^2
Experimental group	32	79.92	10.11	1.36	79.22	5.62*	0.068
Control group	33	72.24	12.22	1.56	73.71		

*$p<0.05$

Table 3 The ANCOVA result of reading creation performance

Group	*N*	Mean	*SD*	Adjusted *SD*	Adjusted mean	*F*	η^2
Experimental group	32	85.35	8.93	1.34	85.02	3.33*	0.072
Control group	33	73.27	12.23	1.88	73.90		

*$p<0.05$

Result

Reading achievement

The present study used a one-way analysis of covariance (ANCOVA) to evaluate the differences in reading achievement between the experimental group and the control group. Before the ANCOVA, the homogeneity of variance assumption and the homogeneity of regression coefficients were tested. For reading achievement, Levene's test for equality of variances was not significant ($F=3.23$, $p=.14>.05$). Hence, the homogeneity of variance assumption was not violated. Similar results were obtained in the following homogeneity of regression coefficients test ($F=1.73$, $p=.14>.05$). The results mentioned above meant that it was appropriate to employ ANCOVA. Table 2 presents the results of the ANCOVA of the two groups. The results revealed a significant difference ($F=5.62$, $p<.05$) in reading achievement between the experimental group (adjusted mean = 79.22) and the control group (adjusted mean = 73.71). Moreover, the effect size ($\eta 2=0.068>0.059$) represented a moderate effect size. This result further showed that reading with immersive AR learning environments was more helpful for students in improving their reading achievement than conventional reading with AR-based books.

Reading creation performance

The ANCOVA was conducted to confirm the difference in students' reading creation performance between the experimental group and the control group. Before ANCOVA, Levene's test of homogeneity of variances was applied to examine whether variances across samples were equal. The result of this test was not significant ($F=3.15$, $p=.22>.05$), which showed that it was satisfied with the condition of homogeneity of variance. Also, the inspection result of the slope homogeneity test ($F=2.14$, $p=.32>.05$) was checked. After controlling for the influence of pre-test scores on reading creation performance, the scores were 85.02 for the experimental group using reading with immersive AR learning environments and 73.91 for the control group, respectively. The results of ANCOVA were given in Table 3 and showed that there was a significant difference ($F=3.33$, $p<.05$) between

Table 4 The ANCOVA result of reading motivation

Group	*N*	Mean	*SD*	Adjusted *SD*	Adjusted mean	*F*	η^2
Experimental group	32	4.72	0.98	0.08	4.80	9.09^{***}	0.876
Control group	33	3.98	0.88	0.08	4.02		

$^{***}p<0.001$

Table 5 The ANCOVA result of cognitive load

Group	*N*	Mean	*SD*	Adjusted *SD*	Adjusted Mean	*F*	η^2
Experimental group	32	4.81	0.74	0.07	4.81	7.29^{*}	0.068
Control group	33	4.12	0.99	0.07	4.14		

$^{*}p<.05$

the two groups of students. Besides, the ANCOVA results gave a moderate effect size with $\eta^2=0.072>0.059$. Consequently, these results indicated that the students in the experimental group achieved significantly better reading creation performance than those in the control group after implementing the reading with immersive AR learning environments. It could be concluded that reading with immersive AR learning environments was particularly helpful to students in enhancing their reading creation performance.

Reading motivation

Regarding hearing-impaired students' motivation, the result of the homogeneity of variance was $F=3.12$, $p=.14>.05$, and the homogeneity of regression coefficients was $F=3.77$, $p=.10>.05$, implying that the ANCOVA could be employed. In comparison with the scores given by the control group (adjusted mean = 4.02), it should be noted that students in the experimental group (adjusted mean = 4.80) gave higher scores for reading motivation. As portrayed in Table 4, a significant difference ($F=9.90$, $p<.001$) was found between the experimental group and the control group, with the η^2 represented a large effect ($\eta^2=0.876>0.138$). This finding implied that those students who read in the immersive AR environment revealed higher degrees of motivation than those who conventionally read with AR-based books.

Cognitive load

Regarding hearing-impaired students' cognitive load, Levene's test for equality of variances was not significant ($F=3.12$, $p=.32>.05$), which indicated that the variances for both groups were assumed to be equal. Also, the inspection result of the slope homogeneity test ($F=3.09$, $p=.08>.05$) was not significant. Therefore, the ANCOVA was conducted. The ANCOVA result indicated that the cognitive load of the two groups showed a significant difference ($F=7.29$, $p<.05$). As shown in Table 5, students in the experimental group (adjusted mean = 4.81) were exposed to more cognitive load than those in the control group (adjusted mean = 4.14). Moreover, the η^2 of the proposed approach was $0.068>0.059$, which indicated a medium effect size. Thus, due to the reverse scoring, it was concluded that the students reading with immersive AR learning environments were subjected to less cognitive load than those conventionally reading with AR-based books.

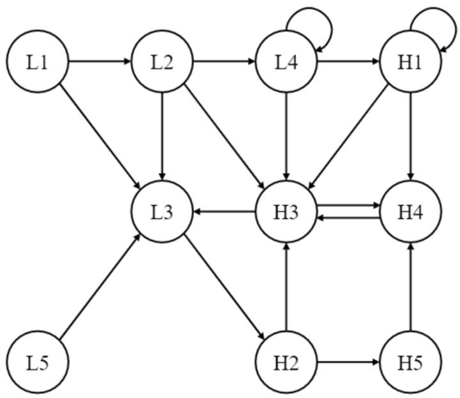
Reading behaviours

According to the coding scheme presented in Table 1, the behaviours of AR-based reading were coded for representing hearing-impaired students' cognitive attainment after reading to explore the behavioural patterns of the experimental group and control group. As shown in Fig. 5, the LSA revealed several important behavioural patterns: H1, H3, H4, and L4, which demonstrated the reading procedures of the students in the experimental group.

Under the proposed approach, the students tended to explore problems according to the reading goals, which would lead to two frequent behavioural patterns: interacting with peers regarding the reading content or exploring problem-solving activities with peers (H1 → H3 and H1 → H4). In particular, the continuity in which the students interacted with peers regarding the reading content ($z = 8.39$, $p < .05$) reached the highest level of significance. Moreover, operating the AR elements of the book from the AR system (L2 → H3), giving comments for help on others' pages (H5 → H4), searching the Internet for more information (L4 → H3 ↔ H4), or reading the feedback of the tasks from the AR system (H2 → H3 ↔ H4), which all led to students interacting with each other. That is, the hearing-impaired students in the experimental group expressed more tendency to reciprocally interact with each other mediated by deep reading strategies in the immersive AR environments than the control group did.

Compared to the behavioural pattern of the experimental group, students in the control group showed different results. Their behavioural patterns consisted of answering the tasks in the AR system and taking personal annotations on the AR-based book in the AR system (Fig. 6). There were only a few connections among each single event in the control group, which involved reading the content of the book, subsequently operating the AR elements, searching the Internet for information on the tasks, and taking notes in the system, which might lead to answering the tasks in the AR system (L1 ↔ L2 → L5 → L4). They would focus on the task module, search the Internet for the tasks, and interact with peers regarding the reading content if required (L3 ↔ L4 → H3). The interaction with peers in problem-solving behavioural patterns (H4) was uncorrelated with other behavioural patterns, suggesting that the students in the control group tended to regard interaction with peers as a

Fig. 5 Behavioural patterns of hearing-impaired students in the experimental group



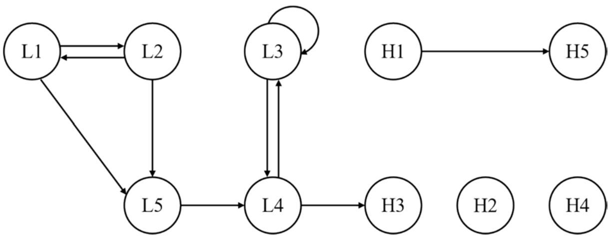


Fig. 6 Behavioural patterns of hearing-impaired students in the control group

task, rarely considering it as a method to foster their higher-level behaviours of cognitive attainment.

Discussion and conclusion

The present study was hence aimed to explore how the hearing-impaired students read books with the proposed immersive AR environment through a quasi-experiment involving multiple dependent variables (e.g., reading achievement, reading creation performance, reading motivation, and cognitive load) and LSA aiming at analysing behavioural patterns. Furthermore, based on the results, associations between students' reading learning outcomes and reading behavioural patterns can be revealed.

In response to research questions 1 and 2, the results indicate that reading in an immersive AR environment can enhance students' reading achievement, reading creation performance, and reading motivation, while reducing their cognitive load. Aldeeb et al. (2024) discovered that AR-based strategies can improve students' outcomes and motivation, which is similar to the findings of this study. In addition, some research has revealed that AR can reduce students' cognitive load due to the contiguity effect (Chen & Mokmin, 2024), user-friendly AR applications, or student proficiency (Ebadi & Ashrafabadi, 2022). However, other research has found that AR increases students' cognitive load due to the AR-based concept association approach, despite this method being able to improve learning achievements (Aldeeb et al., 2024). In this study, the immersive AR learning environment may have reduced the cognitive load of hearing-impaired students due to factors such as student AR training, the spatial contiguity principle, and the ease of operation of the reading system. Specifically, the immersive AR learning environment proposed in this study integrates multiple types of information (e.g., text, images, and videos) into the system, aligning with the spatial contiguity principle proposed by Mayer. Within this system, hearing-impaired students can independently operate the AR elements of the book and take personal annotations on the AR-based book.

The creation performance of hearing-impaired students implied that reading with immersive AR environments stimulated more creativity in students compared to conventional reading with AR-based books. This finding aligns with previous research showing that the application of AR in educational settings can enhance students' creative thinking skills (Yousef, 2021). Specifically, after engaging in an AR creative project, students preferred to ideate and value new ideas (Lin & Wang, 2023). This indicates that immersive AR environments have significant advantages in promoting cognitive development, particularly in stimulating and cultivating creative thinking among hearing-impaired students. Hearing-impaired students can create their works with more individualized expression after reading in immersive AR environments.

The improvement in motivation implied that an immersive AR environment raised hearing-impaired students' willingness to participate in AR reading activities and helped them maintain the reading process. In a previous study, Ebadi and Ashrafabadi (2022) found that AR can enhance learners' willingness to use AR-based approaches. This underscores the need for educators to avoid using AR merely as a standalone tool and instead integrate the immersive environment into their instructional frameworks to enhance hearing-impaired students' willingness, even though AR in isolation can also achieve this outcome.

In response to research question 3, LSA revealed that hearing-impaired students exposed to immersive AR reading environments exhibited distinct reading behaviour patterns and characteristics compared to those reading with AR-based books. Simultaneously, the experimental group demonstrated a more diversified sequence of high-cognitive-level behaviours than the control group, which is attributable to the different roles that AR resources played in the students' cognitive processes. According to the above literature review, motivation could be cultivated through diverse cognitive processing behaviours (Hidi et al., 2004). For instance, as individuals exhibited more relentless attempt behaviours, their motivation within immersive AR environments became stronger (Chen et al., 2024a, 2024b). The immersive AR reading environments focused on triggering situational motivation through AR, which should continuously stimulate hearing-impaired students to engage in more diversified reading behaviours (e.g., exploring problem-solving activities with peers and interactive feedback with the AR system, reading feedback on the tasks from the AR system, and giving comments for help on others' pages). In this process, physical learning interest stemming from AR materials gradually evolves into mental cognitive motivation (Hidi et al., 2004). In contrast, the AR-based books used by the control group primarily focused on students' acquisition of knowledge content from the learning materials, without truly achieving individual knowledge internationalization and cognitive construction through interaction with AR resources, which is supported by the research of Na and Yun (2024). Besides, the LSA results further explained the impact of immersive reading on cognitive load in hearing-impaired students. In the control group, the only high-level cognitive attainment sequences significantly identified were L4 → H3 and H1 → H5.

In conclusion, based on the abovementioned findings, this study further proposed the immersive reading strategy for stimulating hearing-impaired students' significantly deep reading learning. Initially, the strategy underscores the cultivation of self-regulated reading, empowering these students with autonomy throughout the AR book reading process. This autonomy serves as a foundational step towards immersive AR reading, fostering an initiative for reading and adhering to self-directed learning guidance, echoing Kerawalla et al. (2006) findings. Subsequently, experiential exploration within immersive AR environments has emerged as a pivotal strategy to bolster reading comprehension among hearing-impaired students. This exploration entails students engaging with AR-based immersive resources under the guided exploration of teachers, aligning with the perspectives presented by Lin et al. (2023) and Hwang et al. (2018). Furthermore, within immersive environments, the focus on enhancing knowledge building and creative reading tasks for hearing-impaired students revolves around expressive and creative construction. This stage marks students' active participation in the reading community, where they exchange ideas and create works guided by AR manipulation principles and reading scaffolds. Lastly, integrating a diverse array of reading activities into immersive strategies underscores the importance of pluralism. In this context, pluralism signifies the development of a profound understanding and multiple, inclusive perspectives of reading materials through varied learning approaches among students during the AR immersive learning journey.

Implications and limitations

The findings of this study have three key implications, providing valuable suggestions for educators and policymakers to enhance the learning experiences of hearing-impaired students. First, this study highlights the need to integrate collaborative and interactive elements into AR-based learning environments for hearing-impaired students. Educators can design group tasks leveraging AR content to promote peer interaction and problem-solving, thus enhancing engagement and comprehension. Policymakers should support this by training teachers to create inclusive, collaborative AR learning settings and ensuring adequate resources for such implementations. Second, the proposed DEEP learning strategy provides a structured approach to fostering self-regulated reading and creativity. Teachers are encouraged to incorporate scaffolding methods, such as guided exploration and real-time feedback, to help students overcome cognitive and social challenges. Policymakers can include AR-based pedagogy in teacher training programs to ensure the effective implementation of these strategies. Third, this study underscores the importance of establishing systemic frameworks to integrate AR technologies in inclusive education. Policymakers should foster partnerships among schools, developers, and researchers to scale AR-based tools for diverse learning contexts. Such initiatives can bridge resource gaps and promote equity in education for hearing-impaired students.

This research contributes to understanding how immersive AR environments can be tailored to support students with hearing impairment. By integrating scaffolding techniques and interactive elements, it demonstrates how AR can address specific learning needs. Furthermore, the study encourages exploration of AR's potential to foster broader cognitive skills, such as critical thinking and problem-solving, especially for hearing-impaired student populations. The DEEP learning strategy provides a model for interdisciplinary collaboration, highlighting how AR tools can enhance personalization and inclusivity in education.

Some limitations were worth to be noted in this study. First, the sample size was limited in southeast China in the present study. Future studies can be conducted on other hearing-impaired students with diverse cultural backgrounds and larger sample sizes. Second, although the effect of immersive AR learning environments on students' reading achievement, perceptions, and behaviours has been verified, there is still a need to test its effectiveness for a more extended period. Third, this study measured the hearing-impaired students' reading achievement, perceptions, and behaviours as crucial factors. The follow-up studies could take other factors (e.g., higher-order thinking and problem-solving) into account to prove the effectiveness of the proposed environment in promoting hearing-impaired students' reading.

Acknowledgements The authors express their gratitude to the anonymous reviewers and editors for their helpful comments about this paper. This work was supported by The National Natural Science Foundation of China [Grant Number 62007010] and The Special Funds of Climbing Program regarding the Cultivation of Guangdong College Students' Scientific and Technological Innovation "Research on Mechanisms of Digital Transformation Enabling Equity in Compulsory Education" [Grant Number pdjh2024a114].

Author contributions X-FL: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing. XH: Writing—Original Draft, Writing—Review & Editing. XX: Writing—Original Draft, Writing—Review & Editing. JM: Writing—Original Draft, Writing—Review & Editing. WZ: Writing—Original Draft, Writing—Review & Editing. YZ: Writing—Original Draft, Writing—Review & Editing. WL: Writing—Original Draft, Writing—Review & Editing.

Funding All authors have confirmed that no partial financial support was received.

Declarations

Conflict of interest There is no potential conflict of interest between the authors in this study.

Ethical approval The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Academic ethics review committee of South China Normal University (protocol code IRB-SCNU-EIT-2021-016).

Employment There is no recent employment of any author by any person or organization.

References

Aldeeb, F. H., Sallabi, O. M., Elaish, M. M., & Hwang, G. (2024). Enhancing students' learning achievements, self-efficacy, and motivation using mobile augmented reality. *Journal of Computer Assisted Learning, 40*(4), 1823–1837. https://doi.org/10.1111/jcal.12989

Anderson, L. W., & Krathwohl (Eds.). (2001). *A Taxonomy for learning, teaching, and assessing: A revision of bloom' s taxonomy of educational objectives*. Addison Wesley Longman.

Assaly, I., & Jabarin, A. (2021). Arab Israeli EFL teachers' perceptions and practices vis-à-vis teaching higher-order thinking skills: A complicated relationship. *Language Teaching Research*. https://doi.org/10.1177/13621688211032426

Bakeman, R., & Gottman, J. M. (1997). *Observing interaction: An introduction to sequential analysis*. Cambridge University Press. https://doi.org/10.2307/1269577

Chen, C. H., Chan, W. P., Huang, K., & Liao, C. W. (2022). Supporting informal science learning with metacognitive scaffolding and augmented reality: Effects on science knowledge, intrinsic motivation, and cognitive load. *Research in Science & Technological Education*. https://doi.org/10.1080/02635143.2022.2032629

Chen, G. D., & Chao, P. Y. (2008). Augmenting traditional books with context-aware learning supports from online learning communities. *Educational Technology & Society, 11*(2), 27–40.

Chen, J., & Mokmin, N. A. M. (2024). Enhancing primary school students' performance, flow state, and cognitive load in visual arts education through the integration of augmented reality technology in a card game. *Education and Information Technologies*. https://doi.org/10.1007/s10639-024-12456-x

Chen, M., Wu, L., Li, B., & Liu, Y. (2024b). Behavioural patterns associated with solving ill-defined complex problems from a multidimensional perspective: Perception, cognition, metacognition, and motivation. *Educational Technology & Society, 27*(4), 171–190.

Cheng, K. H. (2019). Parents' user experiences of augmented reality book reading: Perceptions, expectations, and intentions. *Educational Technology Research and Development, 67*(2), 303–315. https://doi.org/10.1007/s11423-018-9611-0

Cohen, J. (1960). A coeffcient of agreement for nominal scales. *Educational and Psychological Measurement, 20*(1), 37–46. https://doi.org/10.1177/001316446002000104

Cotán, A., Carballo, R., & Spinola-Elias, Y. (2021). Giving a voice to the best faculty members: Benefits of digital resources for the inclusion of all students in arts and humanities. *International Journal of Inclusive Education*. https://doi.org/10.1080/13603116.2021.1991492

Del Pezo Izaguirre, E., Abasolo, M. J., & Collazos, C. A. (2021). Educational methodologies for hearing impaired children supported by mobile technology and extended reality: Systematic analysis of literature. *IEEE Ibero-American Journal of Learning Technologies, 16*(4), 410–418. https://doi.org/10.1109/rita.2021.3135202

Ebadi, S., & Ashrafabadi, F. (2022). An exploration into the impact of augmented reality on EFL learners' reading comprehension. *Education and Information Technologies, 27*(7), 9745–9765. https://doi.org/10.1007/s10639-022-11021-8

Elawady, S., Afsah, O., Elshawaf, W., & Abou-Elsaad, T. (2019). Developing a functional assessment tool for the auditory performance of Arabic-speaking Egyptian hearing impaired children. *International Journal of Pediatric Otorhinolaryngology, 127*, Article 109678. https://doi.org/10.1016/j.ijporl.2019.109678

Elliott, J. (1991). *Action research for educational change*. Open University Press.

Escudeiro, P., Escudeiro, N., & Gouveia, M. C. (2022). A chemistry inclusive and educational serious game. In *2022 31st Annual Conference of the European Association for Education in Electrical and Information Engineering (EAEEIE)* (pp. 1–6). IEEE. https://doi.org/10.1109/eaeeie54893.2022.9820516

Fernández-Batanero, J. M., Montenegro-Rueda, M., Fernández-Cerero, J., & García-Martínez, I. (2022). Assistive technology for the inclusion of students with disabilities: A systematic review. *Educational Technology Research and Development, 70*(5), 1911–1930. https://doi.org/10.1007/s11423-022-10127-7

Guthrie, J. T., & Klauda, S. L. (2014). Effects of classroom practices on reading comprehension, engagement, and motivations for adolescents. *Reading Research Quarterly, 49*(4), 387–416. https://doi.org/10.1002/rrq.81

Han, I., Ryu, J., & Kim, M. (2017). Prototyping training program in immersive virtual learning environment with head mounted displays and touchless interfaces for hearing-impaired learners. *Educational Technology International, 18*(1), 49–71. https://doi.org/10.23095/ETI.2017.18.1.049

Herrera, S. I., Manresa-Yee, C., & Sanz, C. V. (2021). Mobile learning for hearing-impaired children: Review and analysis. *Universal Access in the Information Society*. https://doi.org/10.1007/s10209-021-00841-z

Hidi, S., & Renninger, K. A. (2006). The four-phase model of interest development. *Educational Psychologist, 41*(2), 111–127. https://doi.org/10.1207/s15326985ep4102_4

Hidi, S., Renninger, S., & Krapp, A. (2004). *Interest, a motivational variable that combines affective and cognitive functioning. In motivation, emotion, and cognition* (pp. 103–130). Routledge.

Hsieh, C. Y. (2023). Research on online inclusive education in Taiwan in the era of COVID-19. *International Journal of Inclusive Education*. https://doi.org/10.1080/13603116.2023.2216230

Huang, T. C., Shu, Y., Yeh, T. C., & Zeng, P. Y. (2016). Get lost in the library? An innovative application of augmented reality and indoor positioning technologies. *Electronic Library, 34*(1), 99–115. https://doi.org/10.1108/el-08-2014-0148

Hwang, G. J., Chang, S. C., Chen, P. Y., & Chen, X. Y. (2018). Effects of integrating an active learning-promoting mechanism into location-based real-world learning environments on students' learning performances and behaviours. *Educational Technology Research and Development, 66*(2), 451–474. https://doi.org/10.1007/s11423-018-9611-0

Ibanez, M. B., Portillo, A. U., Cabada, R. Z., & Btarron, M. L. (2020). Impact of augmented reality technology on academic achievement and motivation of students from public and private Mexican schools. A case study in a middle-school geometry course. *Computers & Education, 145*, 103734. https://doi.org/10.1016/j.compedu.2019.103734

Kerawalla, L., Luckin, R., Seljeflot, S., & Woolard, A. (2006). "Making it real": Exploring the potential of augmented reality for teaching primary school science. *Virtual Reality, 10*(3), 136–174. https://doi.org/10.1007/s10055-006-0036-4

Krasavina, Y., Serebryakova, Y., Ponomarenko, E., & Zhuykova, O. (2019). Research-based teaching of hearing-impaired students. *ARPHA Proceedings, 1*, 1789–2180. https://doi.org/10.3897/ap.1.e1316

Lai, A. F., Chen, C. H., & Lee, G. Y. (2019). An augmented reality-based learning approach to enhancing students' science reading performances from the perspective of the cognitive load theory. *British Journal of Educational Technology, 50*(1), 232–247. https://doi.org/10.1111/bjet.12716

Lin, X.-F., Hwang, G.-J., Wang, J., Zhou, Y., Li, W., Liu, J., & Liang, Z.-M. (2023). Effects of a contextualised reflective mechanism-based augmented reality learning model on students' scientific inquiry learning performances, behavioural patterns, and higher order thinking. *Interactive Learning Environments, 31*(10), 6931–6951.

Lin, Y., & Wang, H. (2023). Applying augmented reality in a university English class: Learners' perceptions of creativity and learning motivation. *Innovation in Language Learning and Teaching, 17*(2), 291–305. https://doi.org/10.1080/17501229.2022.2040513

Liu, C. C., Wu, L. Y., Chen, Z. M., Tsai, C. C., & Lin, H. M. (2014). The effect of story grammars on creative self-efficacy and digital storytelling. *Journal of Computer Assisted Learning, 30*(5), 450–464. https://doi.org/10.1111/jcal.12059

Luangrungruang, T., & Kokaew, U. (2018). Applying universal design for learning in augmented reality education guidance for hearing impaired student. In *2018 5th International Conference on Advanced Informatics: Concept Theory and Applications (ICAICTA)* (pp. 250–255). IEEE. https://doi.org/10.1109/ICAICTA.2018.8541294

Luangrungruang, T., & Kokaew, U. (2022). E-learning model to identify the learning tyles of hearing-impaired students. *Sustainability, 14*(20), 13280. https://doi.org/10.3390/su142013280

Mullis, I. V., Martin, M. O., & Sainsbury, M. (2016). *PIRLS 2016 reading framework* (pp. 11–29). PIRLS.

Na, H., & Yun, S. (2024). The effect of augmented reality on K-12 students' motivation: A meta-analysis. *Educational Technology Research and Development*. https://doi.org/10.1007/s11423-024-10385-7

National Assessment Governing Board U. S. Department of education (Ed.) (2019). *Reading framework for the 2019 National Assessment of Education Progress*. https://files.eric.ed.gov/fulltext/ED604485.pdf

Onuigbo, L., Osadebe, N. E., & Achebe, N. E. (2020). Classroom environment required for meeting the information needs of students with hearing impairment in Nigerian universities. *International Journal of Inclusive Education, 24*(3), 266–287. https://doi.org/10.1080/13603116.2018.1459887

Oral, A. Z., & Kalkan, Ö. K. (2024). Deaf and hard of hearing employees: Accessible and AR-based training materials. *Universal Access in the Information Society*. https://doi.org/10.1007/s10209-024-01143-w

Paas, F. G., & van Merriënboer, J. J. (1994). Instructional control of cognitive load in the training of complex cognitive tasks. *Educational Psychology Review, 6*(4), 351–371. https://doi.org/10.1007/BF02213420

Penenory, V. M., Manresa-Yee, C., Riquelme, I., Collazos, C. A., & Fardoun, H. M. (2018). Scoping review of systems to train psychomotor skills in hearing impaired children. *Sensors (Basel), 18*(8), 12. https://doi.org/10.3390/s18082546

Seale, J., Colwell, C., Coughlan, T., Heiman, T., Kaspi-Tsahor, D., & Olenik-Shemesh, D. (2021). 'Dreaming in colour': Disabled higher education students' perspectives on improving design practices that would enable them to benefit from their use of technologies. *Education and Information Technologies, 26*(2), 1687–1719. https://doi.org/10.1007/s10639-020-10329-7

Soogund, N. U. N., & Joseph, M. H. (2019). SignAR: A sign language translator application with augmented reality using text and image recognition. In *2019 IEEE International Conference on Intelligent Techniques in Control, Optimization and Signal Processing* (INCOS) (pp. 1–5). IEEE. https://doi.org/10.1109/incos45849.2019.8951322

Strnadová, I., Danker, J., Dowse, L., & Tso, M. (2023). Supporting students with disability to improve academic, social and emotional, and self-determination and life-skills outcomes: Umbrella review of evidence-based practices. *International Journal of Inclusive Education, 28*(14), 3606–3622. https://doi.org/10.1080/13603116.2023.2221239

Trussell, J. W., Dunagan, J., Kane, J., & Cascioli, T. (2017). The effects of interactive storybook reading with preschoolers who are deaf and hard-of-hearing. *Topics in Early Childhood Special Education, 37*(3), 147–163. https://doi.org/10.1177/0271121417720015

Wang, L., Lee, H., & Ju, D. Y. (2019). Impact of digital content on young children's reading interest and concentration for books. *Behaviour & Information Technology, 38*(1), 1–8. https://doi.org/10.1080/0144929x.2018.1502807

Wojciechowski, R., & Cellary, W. (2013). Evaluation of learners' attitude toward learning in ARIES augmented reality environments. *Computers & Education, 68*, 570–585. https://doi.org/10.1016/j.compedu.2013.02.014

Yousef, A. M. F. (2021). Augmented reality assisted learning achievement, motivation, and creativity for children of low-grade in primary school. *Journal of Computer Assisted Learning, 37*(4), 966–977. https://doi.org/10.1111/jcal.12536

Zhou, N., & Yadav, A. (2017). Effects of multimedia story reading and questioning on preschoolers' vocabulary learning, story comprehension and reading engagement. *Educational Technology Research and Development, 65*(6), 1523–1545. https://doi.org/10.1007/s11423-017-9533-2

Dr. Xiao-Fan Lin is currently a Professor at South China Normal University, serving as a doctoral supervisor and Deputy Director of the Guangdong Smart Learning Engineering Technology Research Center. His research achievements have been recognized with numerous awards, including: First Prize of the 9th Outstanding Scientific Research Achievements in Higher Education Institutions (2024); First Prize of the 10th Guangdong Provincial Philosophical and Social Sciences Excellent Achievements Award (2023); National First-Class Undergraduate Course (Ranked Second, 2023); Special/First/Second Prizes of the Guangdong Provincial Philosophical and Social Sciences Excellent Achievements Award (2021, 2019 and 2024, 2017); Special/Second Prizes of the Guangdong Provincial Teaching Achievement Award (2021, 2019); and in

2024, he was recognized as a Top 1% Highly Cited Scholar by CNKI (China National Knowledge Infrastructure). His main research areas are Education Policy, Teacher Education, Curriculum and Teaching, AI Education.

Xiyu Huang is a teacher of Information Science and Technology Curriculum at Guangzhou Foreign Language School (511455 Guangzhou, China) and a postgraduate student at South China Normal University, Guangzhou, China. She is an experienced educator who specializes in online learning and Artificial Intelligence education. She is currently pursuing advanced research on intelligent tutoring systems and digital literacy development.

Xiaoqing Xian is a postgraduate student at South China Normal University, Guangzhou, China. She focuses on augmented reality-assisted learning. Her current research investigates how augmented reality applications enhance student engagement and knowledge retention in wrting.

Jiahao Miao is a postgraduate student at South China Normal University, Guangzhou, China. He investigates learning science and smart education technologies. His recent work examines adaptive problem-solving powered by AI systems.

Wei Zhou is a postgraduate student at South China Normal University, Guangzhou, China. She specializes in teachers' professional development through technology-enhanced learning environments. Her current research analyzes digital competence frameworks for STEM students.

Yilin Zheng is a postgraduate student at South China Normal University, Guangzhou, China. She researches mobile-assisted AI education, with a particular focus on personalized learning pathways and educational data mining.

Wenyi Li is a researcher at the GuangDong Engineering Technology Research Center of Smart Learning, Guangzhou, China. She leads projects on AI education applications, including intelligent assessment systems and ethics in educational AI development.

Authors and Affiliations

Xiao-Fan Lin[1,2] · Xiyu Huang[3] · Xiaoqing Xian[3] · Jiahao Miao[3] · Wei Zhou[3] · Yilin Zheng[3] · Wenyi Li[3]

✉ Xiao-Fan Lin
linxiaofan@m.scnu.edu.cn

1 School of Education Information Technology, Guangdong Provincial Institute of Elementary Education and Information Technology, Guangdong Provincial Engineering and Technologies Research Centre of Smart Learning, South China Normal University, Office 214, 55 Zhongshan Dadao Xi, Guangzhou 510631, China

2 Guangdong Provincial Philosophy and Social Sciences Key Laboratory of Artificial Intelligence and Smart Education, Institute for Artificial Intelligence Education, South China Normal University, Guangzhou 510631, China

3 School of Education Information Technology, South China Normal University, Guangzhou 510631, China