# scientific reports

OPEN

# Design and evaluation of children's education interactive learning system based on human computer interaction technology

Mengru Li[1], Yang Lv[1✉], Yongming Pu[1] & Min Wu[2]

This study aims to develop and evaluate an interactive learning system for children. Through mixed-method research, combined with quantitative and qualitative data analysis, this study provides a comprehensive evaluation of the educational effectiveness of the system. The study involves children in grades 1–6, and data on learning effectiveness before and after using the system are collected through pre-experiments and formal experiments. The results of the quantitative analysis show that after using the system, the average improvement rates for students in grades 1–3 and 4–6 are 24.6% and 22.2% in mathematics and 28.1% and 26.8% in science. The average response time of the system is 1.77 s, with the longest response time being 3.1 s. User satisfaction reaches 94%, and the error rate is 0.2%. These results demonstrate that the developed learning system significantly impacts children's learning effectiveness and optimizing user experience.

Childhood is a critical stage for learning, cognition, and emotional development. Scientific educational methods foster intellectual growth while cultivating positive behaviors and values[1–3]. However, traditional educational methods primarily rely on lectures and textbook content[4,5]. While these methods are effective in imparting basic knowledge, they often fail to engage children's interest, resulting in a lack of enthusiasm for learning[6]. Furthermore, traditional education lacks personalization and struggles to meet the diverse learning needs of children[7–9]. Given that each child has a unique cognitive style, learning pace, and interests, a one-size-fits-all teaching method is insufficient, and there is a need for innovative educational methods to address this diversity[10–12].

In recent years, the rapid development of human-computer interaction (HCI) technology has brought new opportunities to the education field[13–15]. With the application of virtual reality (VR), augmented reality (AR), and speech recognition technologies, the interaction between humans and computers has become more natural and intelligent, providing children with a more interactive and immersive learning experience[16–18]. For example, VR technology can create immersive virtual environments that enhance children's learning interest and increase engagement[19–21]; AR technology can integrate abstract knowledge with the real world, helping children understand complex concepts more intuitively[22–24]; Speech recognition and natural language processing (NLP) technologies enable systems to engage in real-time dialogue and feedback with children, thereby enhancing the interactivity and personalization of learning[25–27]. Despite these advancements, many children's educational products on the market still suffer from insufficient interactivity and lack of personalization, failing to effectively meet the individualized learning needs of children[28,29].

Therefore, this study aims to explore how to leverage advanced HCI technologies to design a children's education system that is both interactive and personalized. The specific objectives are as follows. (1) Through the introduction of gamification elements and multimedia interaction methods, the learning process is more interesting and the active participation of children is stimulated to improve the learning effect; (2) Through data collection and analysis, children's learning habits and knowledge mastery can be understood, providing personalized learning suggestions and feedback; (3) Through experimental design and effect evaluation, the effectiveness of the proposed HCI learning system is verified. Meanwhile, the differences in learning effect

[1]Teachers' College, Chengdu University, Chengdu 628000, China. [2]College of Public Administration, Sichuan University, Chengdu 610065, China. ✉email: 18683625582@163.com

and user experience between the experimental and control groups are compared, and the practical application potential of the system in children's education is discussed.

## Literature review

Given the variations in children's cognitive and developmental stages, traditional "one-size-fits-all" teaching methods struggle to address the unique learning needs of each child[30–32]. With the development of information technology, increasing research has explored how to improve children's education methods using modern technology[33,34]. For instance, Tarihoran & Firmanto (2024)[35] argued that multimedia enriched teaching content through images, videos, animations, and other forms, thus enhancing classroom interest and interactivity. Lidyasari et al. (2023)[36] demonstrated that multimedia teaching effectively enhanced children's learning interests and participation, improving their learning effects. In the education sector, HCI technology applications demonstrated significant potential[37]. For example, Shi et al. (2022)[38] utilized VR technology to create realistic virtual learning environments, allowing children to learn in immersive experiences. Wang et al. (2022)[39] employed AR technology to overlay virtual information onto the real world, aiding children in understanding complex concepts more intuitively. Additionally, Younis et al. (2023)[40] employed speech recognition and NLP technologies to facilitate natural dialogue with children, providing immediate feedback and personalized guidance.

Existing research demonstrates that HCI technology significantly improves educational outcomes and learning experiences. However, many children's educational products on the market are still insufficient regarding interactivity, personalization, and engagement[41]. For example, although the educational software proposed by Paliura & Dimoulas (2022)[42] incorporated multimedia elements, it lacked flexible interactive methods and failed to maintain children's attention over extended periods. Aravantinos et al. (2024)[43] analyzed empirical studies on the use of artificial intelligence (AI) in primary education, particularly for children aged 4 to 12 years. They systematically reviewed the existing literature on the application of AI in primary education, highlighting the potential of AI technology to improve teaching quality and enhance the learning experience. Papadakis (2020)[44] investigated whether there were applications available that provided opportunities for preschool and early childhood learners to develop basic coding and skills.

As evident, despite the significant potential of HCI technologies in enhancing educational outcomes and learning experiences, many existing children's educational products still face challenges related to interactivity, personalization, and engagement[45–47]. For instance, the educational software proposed by Paliura & Dimoulas (2022), though incorporating multimedia elements, lacked flexible interaction methods and struggled to maintain children's attention over extended periods. This reflected the limitations of current educational technologies in sustaining children's engagement and meeting their personalized needs.

This study addresses these issues by developing and evaluating an interactive learning system. Unlike traditional educational tools, the proposed system emphasizes a personalized learning experience by integrating AI technologies that provide real-time feedback and customized learning content. This can better align with the cognitive development needs of children at different age levels. Furthermore, it fills a gap in the existing literature, particularly in evaluating the educational effectiveness for children across different grade levels. Most existing studies focus on a single age group and lack comparative analyses between younger and older students. In contrast, this study presents specific data analysis demonstrating the system's effectiveness across various grade levels, especially in enhancing mathematics and science learning. Through these improvements, this study addresses the deficiencies in educational technology related to personalization, interactivity, and engagement. Concurrently, it provides new directions for future research, particularly in the multi-level application of HCI learning systems and the in-depth exploration of learning effects for children at different age stages. Overall, these additions and extensions can offer a more comprehensive and in-depth perspective for the literature review, showcasing this study's theoretical significance and practical value.

## Research methodology
### AI model and its application

This study aims to design and develop an HCI learning system tailored for children. This system integrates advanced multimedia technologies, including VR and AR elements, to create a dynamic and interactive learning environment. The system's framework is depicted in Fig. 1:

Figure 1 presents the user interface layer, which constitutes the interface through which users directly interact, encompassing all front-end elements, such as buttons, pictures, videos, and interactive games. When designing the user interface layer, particular emphasis should be placed on the user experience for children to ensure that the interface is intuitive and engaging. The interactive logic layer processes users' input (e.g., clicking and dragging) and responds to these actions accordingly. Acting as a bridge between the user interface and back-end data management, the interactive logic layer ensures smooth user operation and real-time data processing. The content management layer is responsible for managing the loading, updating, and storage of learning content; This layer extracts content from the database and sends it to the user interface, as well as handling the storage and recycling of user-generated content. The data management layer is responsible for storing, querying, updating, and deleting all data within the application, ensuring the security and integrity of the data. The database system functions as the foundational data warehouse, supporting the upper data requirements and ensuring data security.

The user interface serves as the core component of the HCI system, particularly in children's learning systems. The specific design is presented in Fig. 2.

The interaction logic constitutes one of the core components, determining how users, especially children, interact with the system and how the system responds to user operations. The key design consideration for
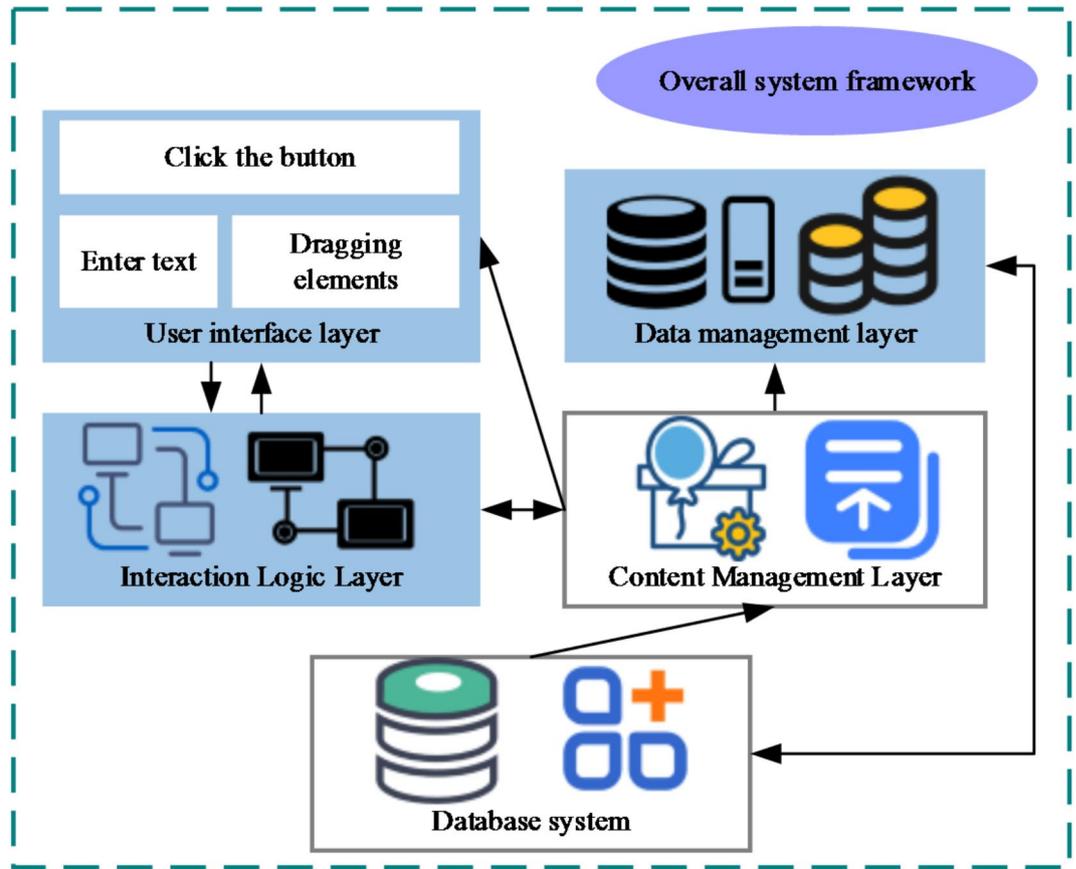
**Fig. 1**. The framework of the HCI learning system: An overview of the system architecture and key components.
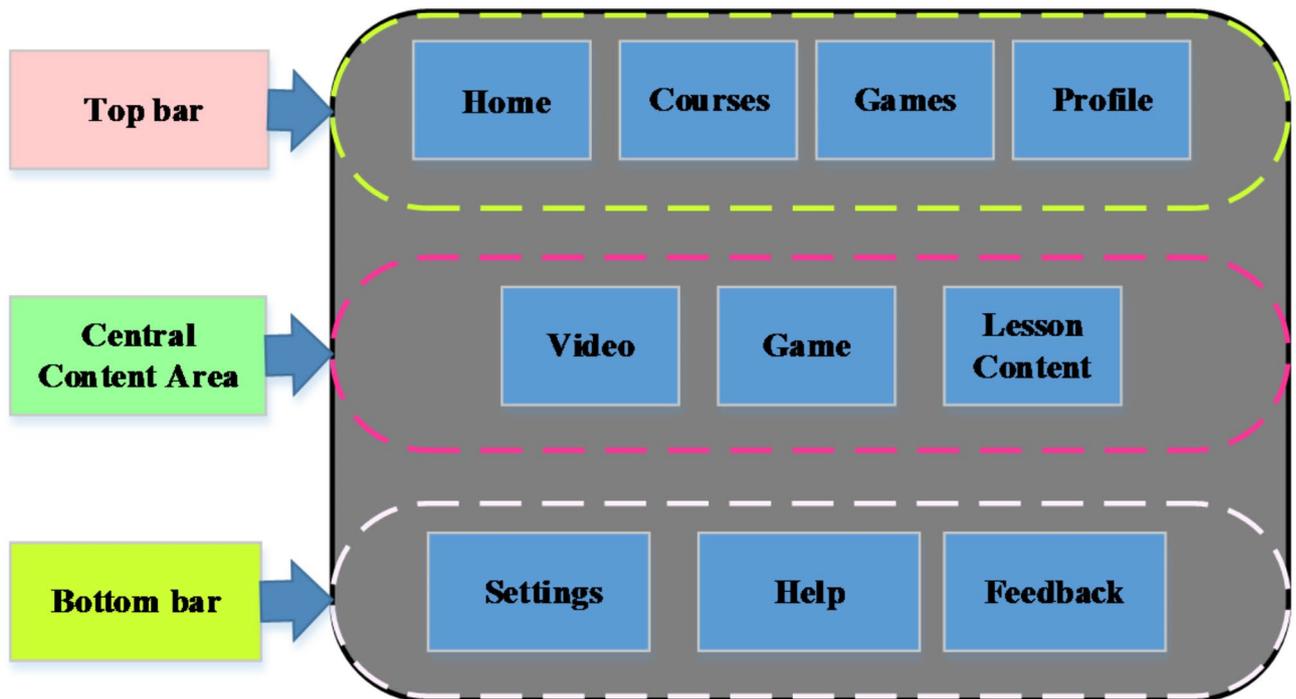


**Fig. 2**. HCI learning system user interface schematic: Visual representation of the main user interaction elements and interface design.

this component is to ensure intuitive operation and rapid response to accommodate children's cognitive and operational abilities. Initially, the system is designed in an event-driven mode, enabling real-time responses to users' inputs (such as clicking, sliding, etc.). This design allows the system to capture and process every user action in real-time, ensuring a seamless interactive experience. Subsequently, the system incorporates a feedback mechanism that provides immediate and clear responses to each user's operation. Such feedback encompasses sound prompts, visual animations, or vibrations, aiding children in understanding that their actions have been recognized and executed by the system. For instance, when a child completes a drag-and-drop action in a jigsaw puzzle, the system can offer feedback by emitting a sound signal of "success" and displaying a green checkmark.

Moreover, the back-end data management system serves as the infrastructure supporting the entire learning platform, responsible for data storage, user management, and content updates. Firstly, a multi-level database architecture is developed to store user information, learning progress, interactive data, and other relevant data. Database design must consider data security, access efficiency, scalability, and other factors. Secondly, the system server must efficiently handle a high volume of requests from the user interface while ensuring the stability and security of data transmission.

Finally, customizing the development of educational content is crucial. Thus, this study focuses on creating appropriate educational materials tailored to children of varying ages. Meanwhile, educational content should be stratified and classified according to children's age and learning ability, ensuring that each age group receives materials tailored to their cognitive level. Additionally, VR and AR technologies offer children an immersive learning experience. The virtual environment and enhanced visual effects also stimulate children's interest in learning and increase their sense of participation.

### User participation and feedback mechanism

To ensure continuous improvement and alignment with the actual needs of end users, this study has established a comprehensive user participation and feedback mechanism for the proposed learning system. The specific feedback strategy is revealed in Fig. 3.

Figure 3 illustrates how these mechanisms combine various methods to encourage users' active participation and systematically collect and utilize their feedback to optimize the system. Initially, a real-time feedback tool is integrated into the system, allowing users to submit feedback instantly upon encountering any problems or suggestions during use. This is facilitated by a prominent "feedback" button in the user interface, enabling users to swiftly provide problem descriptions, suggestions, or screenshots of related issues. The received feedback is automatically categorized. For simple or urgent problems, the system either automatically responds or promptly notifies the technical support team to ensure quick resolution. This instant response mechanism enhances user satisfaction and mitigates potential inconvenience.
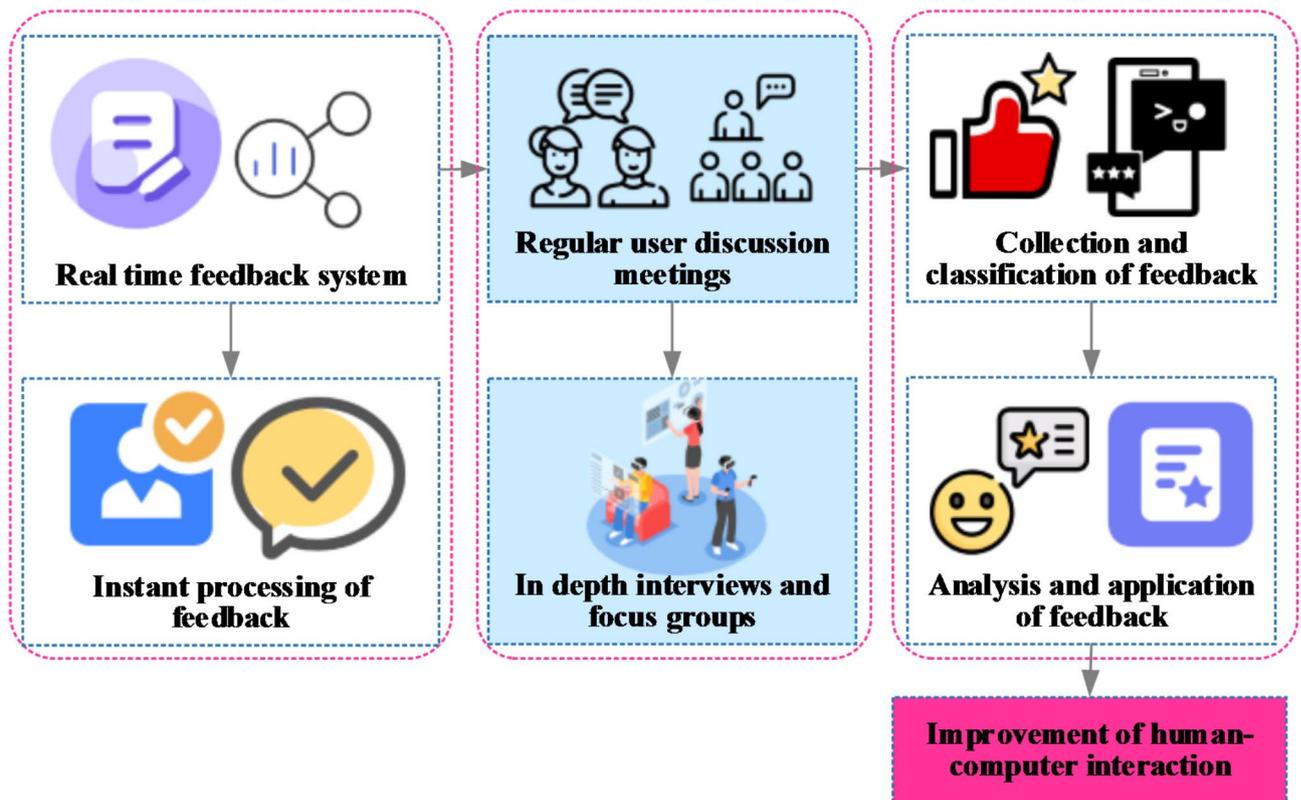


**Fig. 3**. User participation and feedback mechanism: Diagram of the user interface, feedback flow, and data collection process in the HCI learning system.

This study regularly conducts user seminars to gain a deeper understanding of users' needs and experiences. The goal is to engage directly with users, gather their feedback, and allow the design and technical teams to hear their perspectives firsthand. All collected feedback can be systematically sorted and classified. Subsequently, this study analyzes the classified feedback data in detail, identifying the main problems and areas for improvement that users prioritize. Lastly, based on these insights, the design team refines and optimizes the HCI interface and logic. Overall, through this continuous iterative process, this study continually enhances the usability and user experience of the system, ensuring that each update effectively meets users' needs[48].

### Data collection and experimental design

To comprehensively assess the effectiveness of the developed learning system, this study adopts a mixed research framework, combining quantitative and qualitative research methods. The quantitative research component begins with preliminary and formal experimental designs. After the system development is completed, a preliminary experiment is first conducted to evaluate the system's basic functions and its initial educational impact. The preliminary experiment typically involves a small number of users and aims to quickly gather feedback for system optimization. Subsequently, a more systematic formal experiment is conducted, establishing a control group and an experimental group, to scientifically evaluate the actual impact of the learning system on children's learning effects.

In terms of experimental design, the research team employs random assignment to divide participants into an experimental group and a control group. The experimental group uses the developed interactive learning system, while the control group follows traditional teaching methods. The primary objective of the experiment is to evaluate the system's effectiveness in mathematics and science learning, specifically measuring changes in learning effects through data such as test scores, task completion time, and error rates. Furthermore, to ensure the scientific rigor of the experiment, balanced sample sizes are designed to ensure statistical significance and reliability of the results. Strict control measures are also implemented to ensure the accuracy and validity of the experimental results. For instance, baseline learning levels between the experimental and control groups are compared through pre-experiment tests assessing participants' initial learning abilities. Additionally, during the experiment, efforts are made to maintain consistency in the experimental environment, learning time, and other variables, ensuring that these factors do not influence the results.

Regarding data collection tools, standardized testing instruments measure students' learning effects. The test content primarily focuses on foundational knowledge in mathematics and science, with pre-tests and post-tests employed to assess the impact of the system on students' learning. Furthermore, data on task completion times and error rates during system use are collected to explore the system's response efficiency and user operational accuracy. To ensure data accuracy, all test data are analyzed using statistical software. Meanwhile, descriptive statistics, hypothesis testing, effect size analysis, and other methods are employed to evaluate the significance of learning effects and their practical application.

The qualitative research component involves organizing focus group discussions to collect direct feedback from children, parents, and educators regarding the learning system. The purpose of the focus group discussions is to gain insights from multiple perspectives on the strengths and weaknesses of the system in actual use. In addition, the research team conducts in-depth interviews to gather more detailed feedback from individual users, particularly regarding their experiences with the system, responses to the interaction design, system usability, and any challenges encountered. In the area of HCI, this study focuses on user feedback concerning the system's interaction design, analyzing usability and user experience through observational and interview data, to further refine the system design. Beyond traditional self-reported satisfaction surveys, the study also incorporates the System Usability Scale (SUS) and objective records of task completion time. These objective data are triangulated with self-reported user feedback, thereby enhancing the reliability of the user experience evaluation. Through these comprehensive evaluation methods, a more holistic understanding of users' reactions to the system is obtained, ensuring the accuracy and validity of the assessment results.

To ensure the legality and ethics of this study, all children participating in the experiment obtained informed consent from their guardians in advance by signing the consent form. For data collection, the research team designs a series of educational activities and tests to gather children's performance data before and after using the system. The experiment involves children aged 7 to 12 years old, and the collected data includes the following three aspects: (1) Learning progress record: The system automatically records children's learning progress and activity participation. (2) Interactive behavior data: By tracking and recording various interactive behaviors (e.g., clicking, dragging, answering questions, etc.) in the learning system, the research team analyzes children's learning habits and preferences. (3) Feedback from educators and parents: The research team regularly collects feedback from educators and parents regarding children's learning effects and their experience using the system, administering it through oral or written questionnaires.

The sample size for the experiment is 100 participants, encompassing students of different ages, genders, academic backgrounds, and family environments, ensuring the research findings' representativeness and broad applicability. The experiment involved students from multiple grade levels and both genders to balance distribution across different groups. In addition, the sample is appropriately stratified to guarantee a reasonable allocation of students from various ages, grades, and genders between the experimental and control groups, further enhancing the generalizability and diversity of the study's results.

To further strengthen the transparency and rigor of the ethical framework, particular attention was given to the privacy protection of children's data. During the data collection process, all personal information was strictly anonymized and used solely for academic analysis within this study. The research data included children's academic performance, interaction behaviors, and other relevant information, but this was never linked to participants' identities to ensure confidentiality. All data storage and transmission were encrypted to prevent

| Category | Equipment/software | Specification/version | Adoption number |
|---|---|---|---|
| Hardware | Computer system | High performance CPU (Intel i7), 16GB RAM, SSD 512GB | 10 |
| | VR equipment | Oculus Rift S, resolution ratio 2560×1440 | 5 |
| | AR tool | Apple iPad Pro 12.9 inch, 256GB | 5 |
| | Audio and video equipment | Canon XA11, 1080p HD; Blue Yeti USBmicrophone | 3 |
| Software | Operating system | Windows 10 Pro, 64-bit | 10 |
| | Learning management system | Moodle 3.9 | 1 |
| | Data analysis tool | SPSS Statistics 26, Python 3.8 | 10 |

**Table 1**. Experimental configuration.

| Parameter category | Parameter name | Set value |
|---|---|---|
| System performance parameters | FPS | 60 FPS |
| User interface parameters | Response time | ≤200ms |
| Data acquisition parameters | Data sampling rate | 100 Hz |
| Learning content parameters | Content adaptive adjustment frequency | Check every 5 min. |
| Security and privacy parameters | DES | AES 256 bit |
| Network parameter | Network delay | ≤50ms |
| Experimental control parameters | Test times | 3 times |
| Educational content parameters | Educational content renewal cycle | Once a week≤200ms |

**Table 2**. Parameter configuration.

information leakage. Furthermore, parents were fully informed in the consent form about the scope and purpose of data usage and were granted the right to access or delete their children's data at any time.

In terms of assessing long-term risks, corresponding measures were implemented to prevent the negative effects of overreliance on technology. The research team designed a tracking mechanism to regularly survey and evaluate the learning behaviors and social interactions of children following their use of the system. Particular attention was given to the potential negative impacts of technology use on children's social skills and physical activity. Therefore, during the experiment, the system usage time for each child was kept within a reasonable range, and traditional learning methods and real-world activities were integrated to avoid fostering an excessive dependency on technology.

## Experimental results and discussion
### Experimental environment and parameters setting
Table 1 exhibits the experimental environment used in this study, including hardware configuration and software configuration:

Table 2 shows in detail the parameter settings involved in the experiment, ensuring the standardization and reproducibility of the experimental conditions:

### Performance evaluation
This study employs the following indicators (promotion rate of learning effect, system response time, user satisfaction, error rate, and interactive experience score) to evaluate the proposed interactive system's performance. The promotion rate of learning effect measures the percentage change in grades before and after learning in different educational contents and age groups. System response time is based on the system's response time under various operations and load conditions. User satisfaction is assessed from the perspectives of children, educators, and parents. Error rate refers to the operation error frequency of diverse modules in the system. The interactive experience score is based on different modules, user types, interactive fluency, and intuitive scores. The improvement of the learning effect is shown in Fig. 4:

In Fig. 4, within grades 1–3, science subjects exhibit the highest promotion rate, reaching 28.1%. This suggests that the learning system is particularly effective in providing experimental and practical content, aiding younger students in better comprehending abstract scientific concepts. In grades 4–6, the promotion rate of social science is the highest, at 26.8%. For students of this age, the system may effectively enhance their understanding and interest in social science through interactive content and case studies. Mathematics and Chinese demonstrate a consistent promotion rate in both grade groups, indicating the learning system's wide applicability and effectiveness in these fundamental subjects. The promotion rate of English is slightly lower in grades 1–3, possibly due to the need for more practice and immersion in the language environment in language learning.

Further statistical analysis on the improvement of learning effects is outlined in Table 3:

According to the statistical analysis results in Table 3, the improvement in learning effects across all subjects is significant in different grade groups. The p-values from the t-test are all less than 0.01, indicating that the system's impact on learning effects is statistically significant. Cohen's d is used to measure the effect size. In
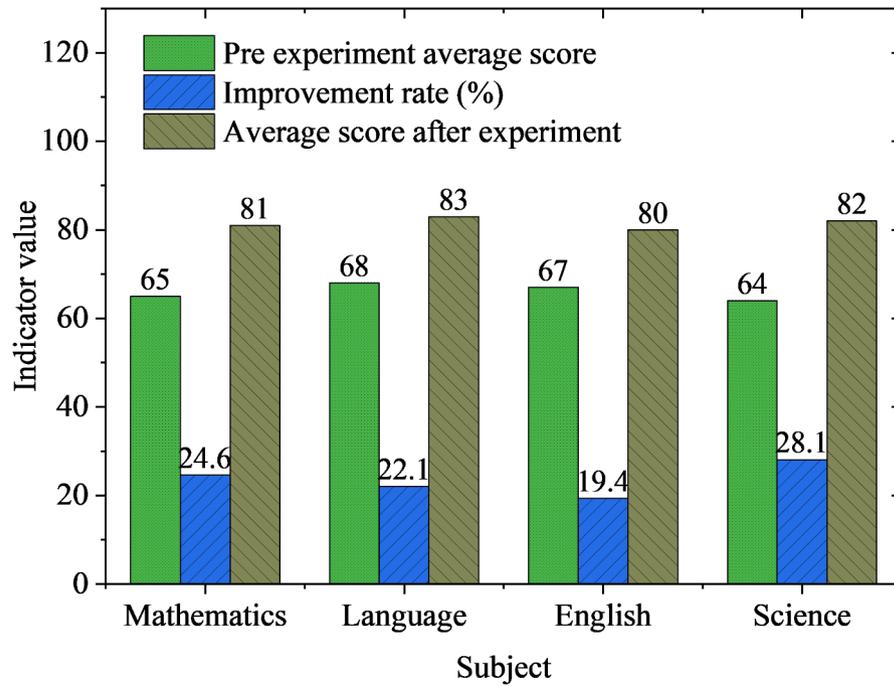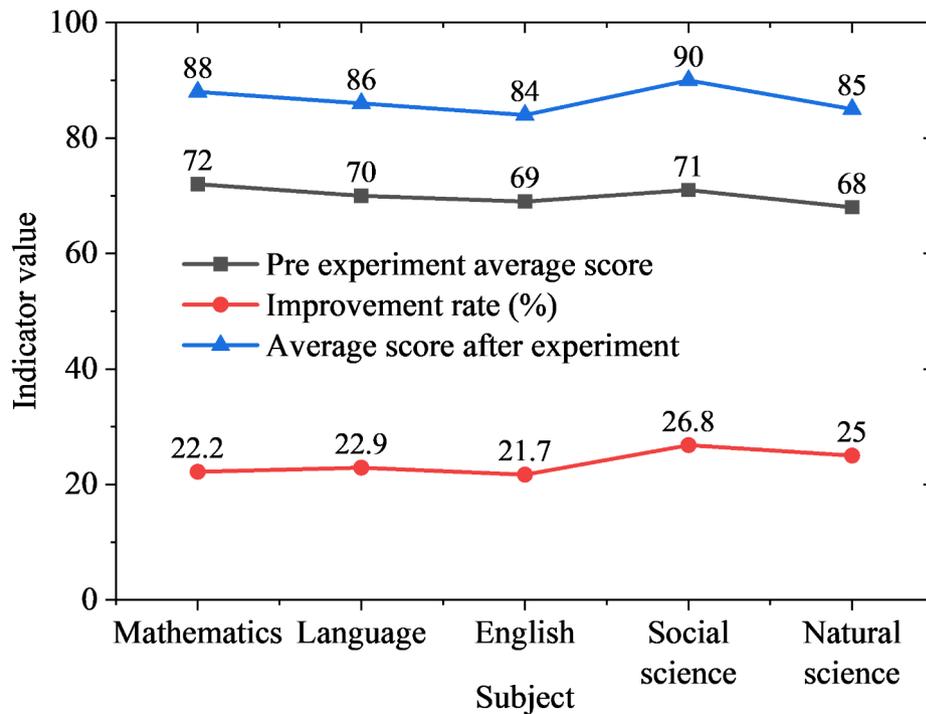
**Fig. 4.** The improvement rate of children's learning effect at different ages (**a**. Grades 1–3; **b**. Grades 4–6).

the grade groups 1–3, the effect size for science (d = 0.67) is large, suggesting that the learning system has a significant impact on improving learning effects in this subject. Mathematics (d = 0.56) and Chinese (d = 0.53) also exhibit moderate effect sizes, confirming the system's effectiveness in these subjects. An effect size greater than 0.5 is generally considered to represent a moderate or stronger effect, illustrating that the application of the learning system has a tangible positive impact on these subjects.

In the grade groups 4–6, the effect size for social science (d = 0.62) is slightly higher than that for mathematics (d = 0.58) and English (d = 0.50). This result can be explained by the differences in content complexity and

| Grade Group | Subject | t-value | p-value | Confidence Interval (95%) | Effect Size (Cohen's d) |
|---|---|---|---|---|---|
| Grades 1–3 | Science | 3.98 | < 0.01 | [22.1, 34.1] | 0.67 |
| Grades 1–3 | Mathematics | 3.42 | < 0.01 | [12.3, 24.5] | 0.56 |
| Grades 1–3 | Chinese | 3.15 | < 0.01 | [11.5, 23.5] | 0.53 |
| Grades 4–6 | social science | 3.72 | < 0.01 | [20.8, 32.8] | 0.62 |
| Grades 4–6 | Mathematics | 3.61 | < 0.01 | [16.2, 28.3] | 0.58 |
| Grades 4–6 | English | 3.03 | < 0.01 | [9.5, 21.8] | 0.50 |

**Table 3**. Statistical analysis of the improvement rate of learning effect.

students' interest in various subjects. For instance, social science may rely more on interactive content and case analysis, making it more responsive to system optimization. Science and social science exhibit more pronounced improvements, particularly in the grade groups 1–3 and 4–6, with the improvement rates and effect sizes being notably significant. The characteristics of these subjects make them more conducive to enhancing students' understanding of abstract concepts when using an interactive learning system. In contrast, English shows relatively weaker improvement in the grade groups 1–3 (d = 0.50), which may be related to the long-term nature of language learning and students' reliance on a language-rich environment. Overall, the learning system demonstrates positive improvements in learning effects across most subjects and grade groups, and the effect size analysis validates this finding.

Figure 5 presents the system response time, comparing the performance of the proposed system with similar HCI systems for children's education from the references[49 and 50].

Figure 5 shows that the proposed system exhibits significant advantages in multiple response time indicators compared to the systems in the references[49 and 50]. First, regarding login response time, the proposed system's 1.7 s is significantly lower than the 2.3 s reported in reference[49] and the 2.1 s in reference[50]. This indicates that the proposed system responds to user login requests more quickly, reducing waiting times during system startup and enhancing the initial user experience. Especially in educational systems, fast login times can improve system acceptability and user satisfaction. Second, in terms of content loading time, the proposed system's 2.2 s is also notably better than the 3.1 s in reference[49] and 3.0 s in reference[50]. This means that the proposed system can load educational content more efficiently, particularly when dealing with large multimedia resources, reducing user wait times and improving learning efficiency. Furthermore, considering interaction response time, the proposed system's 0.45 s is much lower than the 0.8 s in reference[49] and 0.6 s in reference[50], indicating that the proposed system has a faster response time for user interactions. Quick interaction response times are crucial for enhancing the interactivity and user experience of educational systems, especially in educational settings where students and teachers need rapid feedback. Regarding multimedia processing time, the proposed system's 3.1 s is faster than the 3.9 s in reference[49] and 3.7 s in reference[50], demonstrating stronger processing capabilities. The system can quickly handle multimedia content such as audio and video, reducing delays caused by loading large files and improving the efficiency of presenting instructional content. Finally, in terms of test feedback time, the proposed system's 1.4 s is better than the 2.0 s in reference[49] and 1.8 s in reference[50], suggesting that this system provides quicker feedback on students' test results. This improves the timeliness of feedback during the learning process and helps students adjust their learning strategies more quickly.

Overall, the proposed system outperforms the systems in reference[49] and reference[50] on all key indicators, particularly in terms of response time and processing speed. These advantages significantly enhance the user experience and the efficiency of the educational system. This improvement is mainly attributed to optimized backend processing mechanisms, efficient resource management, caching strategies, and smoother user interaction design. All of these enable the system to provide fast and stable services across different usage scenarios, thus improving the effectiveness and quality of educational activities. The probability of system errors is suggested in Fig. 6.

The data in Fig. 6 indicates that the proposed system is superior to the references[49 and 50] in the error rate of all functional modules, particularly in login, content loading, interaction response, and data synchronization. First, regarding the login error rate, the proposed system exhibits significantly lower error rates in the "learning content browsing," "interactive exercises," and "grades and feedback system" modules compared to references[49 and 50]. This indicates that the proposed system has better stability during the user login process, reducing difficulties encountered by users when logging in. In contrast, the error rates in references[49 and 50] are generally higher, especially in the "user settings" and "system management" modules, where the proposed system also shows relatively lower error rates, reflecting the optimized system architecture.
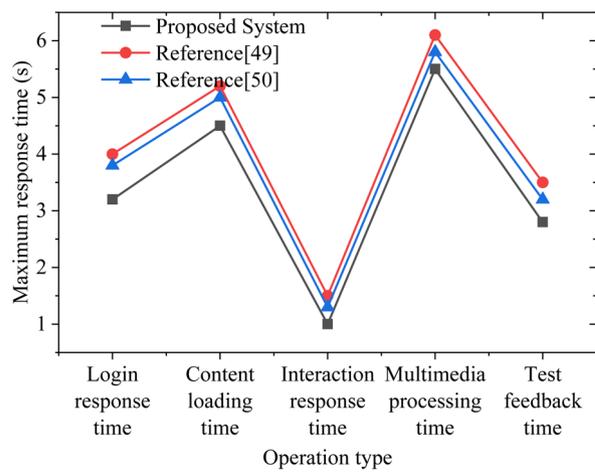
In terms of content loading error rates, the proposed system shows lower error rates in the "learning content browsing" and "interactive exercises" modules than the systems in references[49 and 50]. Particularly in the "grades and feedback system," the proposed system performs exceptionally well. The higher error rates in references[49 and 50] may be related to the complexity of the content-loading modules and the network environment.

For interaction response error rates, the proposed system has a lower error rate in the "learning content browsing" module compared to references[49 and 50], indicating higher accuracy and smoother interaction responses. Especially in the "interactive exercises" and "grades and feedback system" modules, the proposed system continues to outperform both reference systems. The higher interaction response error rates in references[49 and 50] may be attributed to insufficient optimization of their system's response speed and user interface design.
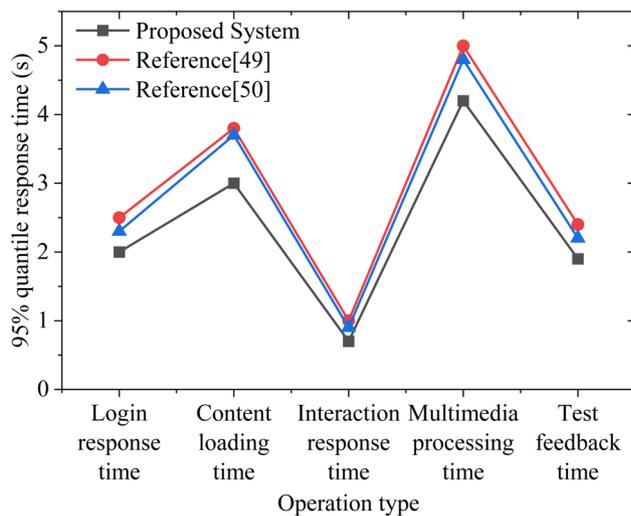
Finally, in terms of data synchronization error rates, the proposed system performs better than references[49 and 50] across all modules, with the most significant differences observed in the "learning content
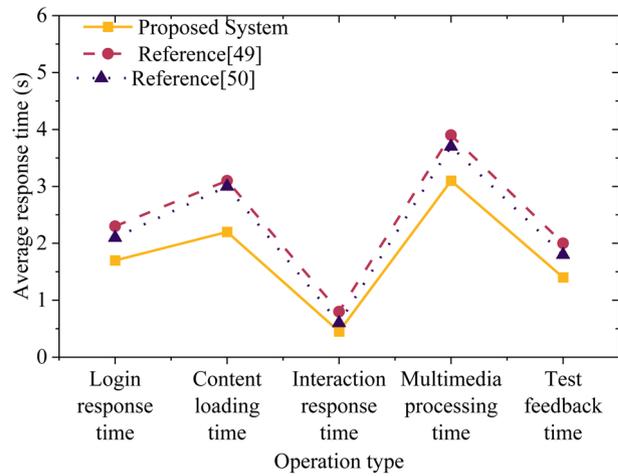
**Fig. 5**. System response time situation (**a**. Average response time; **b**. Maximum response time; **c**. 95% quantile response time).
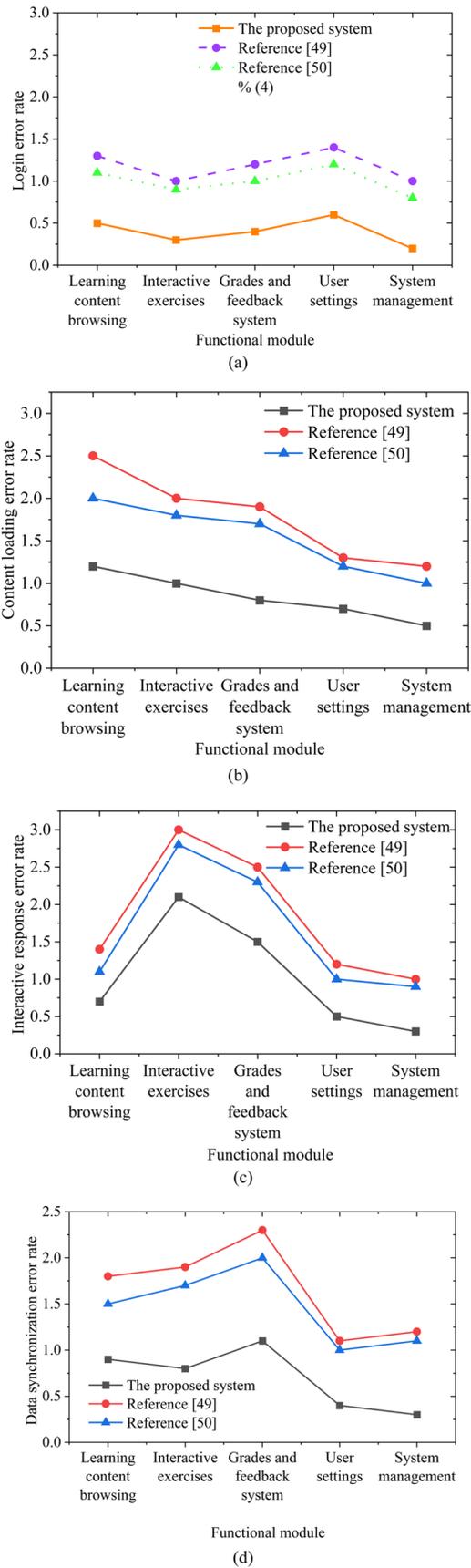
**Fig. 6**. Error rates of the HCI learning system (**a**. Login error rate; **b**. Content loading error rate; **c**. Interaction response error rate; **d**. Data synchronization error rate).
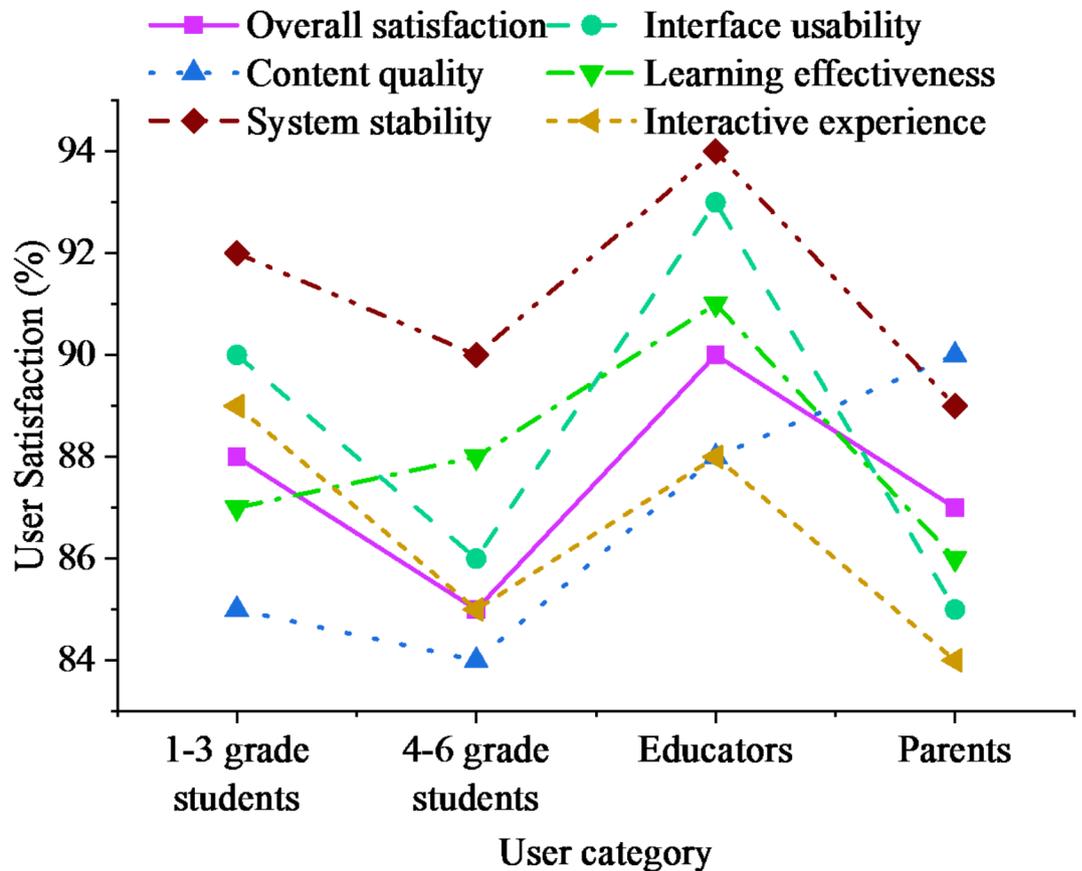
**Fig. 7**. Analysis of user satisfaction survey results.

browsing" and "interactive exercises" modules. This suggests that the proposed system has stronger stability in real-time data updates and synchronization, better handling the synchronization of multiple users and data streams.

In summary, the proposed system shows remarkable advantages over the systems in references[49 and 50] in terms of performance across all functional modules, especially in reducing error rates. Key factors contributing to the system's advantages include optimized system design, data processing, interaction design, and real-time synchronization capabilities, significantly enhancing the user experience. Especially in educational applications, the system's high reliability and low error rates play a critical role in improving learning effects.

Figure 7 presents the survey results regarding different users' satisfaction with the system's use.

In Fig. 7, the overall satisfaction of educators is the highest, reaching 90%. This may be attributed to their ability to better assess the effectiveness of the learning system in teaching, particularly in terms of convenience in teaching management and academic guidance. Students' satisfaction is relatively lower, especially for students in grades 4–6, which could be related to the complexity of the learning content and the increasing system requirements as grade levels advance. Educators report the highest satisfaction with the system's interface usability, at 93%, indicating that the interface design aligns with their operational habits, enabling them to work more efficiently during use. In contrast, parents rate the interface usability slightly lower, at 85%, which may be due to their less frequent use of the system and lower familiarity with the interface design. However, parents rate the content quality the highest, at 90%, reflecting their strong emphasis on educational content, particularly the system's positive impact on improving their children's academic abilities. For students in grades 4–6, their satisfaction with learning effects is 88%, showing that the system effectively delivers instructional content that meets the learning needs of older students. These varied feedbacks suggest that the system's design meets the diverse needs of different users and has substantial educational value, especially in enhancing academic performance and fostering learning motivation.

## Discussion

The experimental results of this study indicate a significant improvement in the learning effect of students in grades 1–3 and 4–6 after using this learning system. This finding aligns with the research of Yousef[51], who demonstrated that using technology-assisted learning tools could effectively enhance students' learning motivation and grades. Furthermore, the subject-specific promotion demonstrated the system's success in content adaptability, supporting Liu et al.'s[52] argument that personalized learning paths could remarkably enhance learning efficiency and outcomes. The system's response time surpassed that of many existing educational technology solutions, according to Tessema & Cavus[53], who highlighted the system's response time as a key factor influencing user

satisfaction and continuous usage willingness. The study's data reveals that the average response time of different operation types falls within the acceptable range for users. The user satisfaction survey's results and the system's error rate data complement each other, as low error rates correspond to high user satisfaction. This finding was consistent with the research of Almaiah & Alyoussef[54], who emphasized that system reliability was crucial to ensuring the effectiveness of educational resources.

As AI ethics receive increasing attention, especially regarding the challenges of privacy protection, data security, and algorithmic bias in educational settings, this study offers an in-depth exploration of HCI and AI technologies within educational technology. meanwhile, it provides valuable insights for future discussions on AI ethics in education. Furthermore, with the rapid development of personalized and adaptive learning technologies, how to utilize emerging technologies to help students from different backgrounds and with varying abilities achieve personalized learning has become an important research direction in education. This study, through its exploration of adaptive learning systems, demonstrates how HCI technology can respond to differentiated student needs, making it highly relevant for practical application.

It can be found that this study demonstrates the performance of the interactive learning system through various evaluation indicators, including improvements in learning effects, system response time, and error rates, all showing positive results. However, there are some limitations in the current research that need further improvement in future studies. First, the sample size and diversity are somewhat limited, as the study primarily focuses on a single educational institution, which may constrain the generalizability of the findings. Future studies should consider expanding the sample size and including participants from various educational backgrounds, regions, and age groups to verify the system's effectiveness in different contexts. Second, the evaluation period in this study is relatively short and may not fully reflect the system's effects over prolonged usage. Future research could employ longitudinal designs to track the system's performance over a longer period to gain a deeper understanding of its sustained impact and identify potential areas for improvement. Third, while this study assesses the system's performance indicators (e.g., response time and error rates) under controlled conditions, the system's performance in real-world environments may vary due to network instability or differing hardware conditions. Therefore, future studies should evaluate the system in real-world environments to ensure its stability and reliability under varying conditions. Moreover, although the system receives positive feedback from educators and parents, there are notable differences in satisfaction among students of different grade levels, especially with older students providing relatively lower feedback. This suggests that the system's usability and learning content may need adjustments based on various age groups. Future research should further explore the factors influencing user satisfaction across diverse groups and refine the system experience accordingly.

## Conclusion
### Research contribution
The main contributions of this study are as follows. (1) Improvement in learning effects: The research results indicate that the proposed system significantly enhances children's academic performance across various subjects, particularly in science and social studies, especially among younger students. The system adapts to the individual learning needs of students, playing a positive role in fostering understanding and engagement, particularly for younger learners. (2) Optimization of user experience: A key contribution of this study is the system design, which thoroughly considers children's operational habits and cognitive characteristics. By designing an intuitive user interface, interactive features, and engaging educational tools, the system provides a learning environment that is easy to use and enhances user satisfaction. This design not only boosts users' motivation to learn but also improves the effectiveness of the learning process by aligning with the cognitive development stages of the target audience. (3) Optimization of response time: Another significant contribution is optimizing the system architecture, resulting in a substantial reduction in response time. This is crucial for minimizing delays in learning and ensuring a smooth learning experience. The system's rapid response time contributes to improved learning efficiency, particularly in tasks that require real-time feedback or interactive exercises. (4) Potential for widespread application: Beyond its direct educational benefits, this study demonstrates the system's potential to expand the scope of interactive learning tools, making it particularly suitable for remote education and personalized learning environments. The system's adaptability across different age groups, subjects, and learning styles makes it a promising tool for future education. This is especially true when it is integrated with advanced technologies such as AI, VR, and AR to support personalized and engaging learning experiences. Consequently, this study advances the understanding of children's interactive learning systems and proposes a scalable model with global application potential. This can be further expanded in fields such as cross-cultural education and long-term learning effects assessment.

### Future works and research limitations
As the study's sample primarily comprises children from a specific region, its findings may not fully generalize to users from other regions or age groups. In addition, due to the study's limited period, the long-term effects of using the learning system may not be fully observed. Hence, future research could consider expanding the scope to include users with diverse cultural and educational backgrounds to explore the applicability and effects of the learning system on a global scale. Simultaneously, future research could explore the application of AI and machine learning technology in personalized learning path design to enhance the learning effectiveness and adaptability of the system.

### Data availability
The datasets used and/or analysed during the current study available from the corresponding author Yang Lv on reasonable request via e-mail 18683625582@163.com.

## References

1. Su, J., Ng, D. T. K. & Chu, S. K. W. Artificial intelligence (AI) literacy in early childhood education: The challenges and opportunities. *Comput. Educ. Artif. Intell.* **4**, 100124 (2023).
2. Su, J & Yang, W. A systematic review of integrating computational thinking in early childhood education. *Comput. Educ. Open.* **4**, 100122 (2023).
3. Zeng, Y., Yang, W. & Bautista, A. Computational thinking in early childhood education: Reviewing the literature and redeveloping the three-dimensional framework. *Educ. Res. Rev.* **39**, 100520 (2023).
4. Ogunyemi, F. T. & Henning, E. From traditional learning to modern education: Understanding the value of play in Africa's childhood development. *South. Afr. J. Educ.* **40**(2), S1–S11 (2020).
5. Zhang, L. Chinese traditional culture education: Implementing the child's position and perspective in the elementary school textbook morality and law. *ECNU Rev. Educ.* **5**(4), 702–719 (2022).
6. Kenanoglu, D. & Duran, M. The effect of traditional games on the language development of pre-school children in pre-school education. *Asian J. Educ. Train.* **7**(1), 74–81 (2021).
7. Kamaruddin, I., Tannady, H. & Aina, M. The efforts to improve children's motoric ability by utilizing the role of traditional games. *J. Educ.* **5**(3), 9736–9740 (2023).
8. Madondo, F. & Tsikira, J. Traditional children's games: Their relevance on skills development among rural Zimbabwean children age 3–8 years. *J. Res. Child. Educ.* **36**(3), 406–420 (2022).
9. Cumbo, B. & Selwyn, N. Using participatory design approaches in educational research. *Int. J. Res. Method Educ.* **45**(1), 60–72 (2022).
10. Johnstone, A. et al. Nature-based early childhood education and children's social, emotional and cognitive development: A mixed-methods systematic review. *Int. J. Environ. Res. Public Health.* **19**(10), 5967 (2022).
11. Bjorklund, D. F. Children's evolved learning abilities and their implications for education. *Educ. Psychol. Rev.* **34**(4), 2243–2273 (2022).
12. Jaenullah, J., Utama, F. & Setiawan, D. Resilience model of the traditional islamic boarding school education system in shaping the morals of student in the midst of modernizing education. Jurnal Kependidikan: Jurnal Hasil Penelitian Dan Kajian Kepustakaan Di Bidang Pendidikan, Pengajaran Dan Pembelajaran, **8**(4): 931–942. (2022).
13. Wang, S. et al. When adaptive learning is effective learning: Comparison of an adaptive learning system to teacher-led instruction. *Interact. Learn. Environ.* **31**(2), 793–803 (2023).
14. Van Mechelen, M. et al. Emerging technologies in K–12 education: A future HCI research agenda. *ACM Trans. Computer-Human Interact.* **30**(3), 1–40 (2023).
15. Lehnert, F. K. et al. Child–computer interaction: From a systematic review towards an integrated understanding of interaction design methods for children. *Int. J. Child-Comput. Interact.* **32**, 100398 (2022).
16. Lin, S. et al. Exploring the relationship between abusive management, self-efficacy and organizational performance in the context of human–machine interaction technology and artificial intelligence with the effect of ergonomics. *Sustainability* **14**(4), 1949. (2022).
17. Zhan, Z. et al. Effect of unplugged programming teaching aids on children's computational thinking and classroom interaction: With respect to Piaget's four stages theory. *J. Educ. Comput. Res.* **60**(5), 1277–1300 (2022).
18. Adem, A., Çakıt, E. & Dağdeviren, M. Selection of suitable distance education platforms based on human–computer interaction criteria under fuzzy environment. *Neural Comput. Appl.* **34**(10), 7919–7931 (2022).
19. Iivari, N. et al. Critical agenda driving child–computer interaction research—taking a stock of the past and envisioning the future. *Int. J. Child-Comput. Interact.* **32**, 100408 (2022).
20. Villena-Taranilla, R. et al. Effects of virtual reality on learning outcomes in K-6 education: A meta-analysis. *Educational Res. Rev.* **35**, 100434 (2022).
21. Passig, D., Tzuriel, D. & Eshel-Kedmi, G. Improving children's cognitive modifiability by dynamic assessment in 3D Immersive Virtual Reality environments. 95296–308 (Computers & Education, 2016).
22. Araiza-Alba, P. et al. The Potential of 360-degree Virtual Reality Videos to Teach water-safety Skills to children. 163104096 (Computers & Education, 2021).
23. Aydoğdu, F. Augmented reality for preschool children: An experience with educational contents. *Br. J. Edu. Technol.* **53**(2), 326–348 (2022).
24. Hassan, S. A., Rahim, T. & Shin, S. Y. ChildAR: An augmented reality-based interactive game for assisting children in their education. *Univ. Access Inf. Soc.* **21**(2), 545–556 (2022).
25. Düzyol, E., Yıldırım, G. & Özyılmaz, G. Investigation of the effect of augmented reality application on preschool children's knowledge of space. *J. Educational Technol. Online Learn.* **5**(1), 190–203 (2022).
26. Xia, K. et al. An intelligent hybrid–integrated system using speech recognition and a 3D display for early childhood education. *Electronics* **10**(15), 1862 (2021).
27. Bhardwaj, V. et al. Automatic speech recognition (asr) systems for children: a systematic literature review. *Appl. Sci.* **12**(9), 4419 (2022).
28. Dalim, C. S. et al. Using augmented reality with speech input for non-native children's language learning. *Int. J. Hum. Comput. Stud.* **134**, 44–64 (2020).
29. Eriksson, E. et al. Teaching for values in human–computer interaction. *Front. Comput. Sci.* **4**, 830736 (2022).
30. Fan, X. & Zhong, X. Artificial intelligence-based creative thinking skill analysis model using human–computer interaction in art design teaching. *Comput. Electr. Eng.* **100**, 107957 (2022).
31. Yıldız, T. Human-computer interaction problem in learning: Could the key be hidden somewhere between social interaction and development of tools?. *Integr. Psychol. Behav. Sci.* **53**(3), 541–557 (2019).
32. Giannakos, M. N. et al. Movement forward: The continued growth of child–computer Interaction research. *Int. J. Child-Comput. Interact.* **26**, 100204 (2020).
33. Tsvyatkova, D. & Storni, C. A review of selected methods, techniques and tools in child–computer Interaction (CCI) developed/adapted to support children's involvement in technology development. *Int. J. Child-Comput. Interact.* **22**, 100148 (2019).
34. Vartiainen, H., Tedre, M. & Valtonen, T. Learning machine learning with very young children: Who is teaching whom?. *Int. J. Child-Comput. Interact.* **25**, 100182 (2020).
35. Tarihoran, E. & Firmanto, A. D. Transforming catechesis with multimedia: Enhancing quality and engagement in religious education. *Ilomata Int. J. Social Sci.* **5**(2), 355–369 (2024).
36. Lidyasari, A. T. et al. The effectiveness of interactive multimedia-based learning methods to increase the motivation of elementary school teachers in the Jsit Kulonprogo environment. *Al-Bidayah: Jurnal Pendidikan Dasar Islam* **15**(1), 41–56. (2023).
37. Jiang, S., Wang, L. & Dong, Y. Application of virtual reality human-computer interaction technology based on the sensor in English teaching. *J. Sensors* **2021**, 1–10. (2021).
38. Shi, A., Wang, Y. & Ding, N. The effect of game–based immersive virtual reality learning environment on learning outcomes: Designing an intrinsic integrated educational game for pre–class learning. *Interact. Learn. Environ.* **30**(4), 721–734 (2022).

39. Wang, R. Application of augmented reality technology in children's picture books based on educational psychology. *Front. Psychol.* **13**, 782958 (2022).
40. Younis, H. A. et al. A systematic literature review on the applications of robots and natural language processing in education. *Electronics* **12**(13), 2864 (2023).
41. Paraschos, P. D. & Koulouriotis, D. E. Game difficulty adaptation and experience personalization: A literature review. *Int. J. Human–Computer Interact.* **39**(1), 1–22 (2023).
42. Palioura, M. & Dimoulas, C. Digital storytelling in education: A transmedia integration approach for the non-developers. *Educ. Sci.* **12**(8), 559 (2022).
43. Aravantinos, S. et al. Educational approaches with AI in primary school settings: a systematic review of the literature available in scopus. *Educ. Sci.* **14**(7), 744 (2024).
44. Papadakis, S. Apps to promote computational thinking concepts and coding skills in children of preschool and pre-primary school age[M]//Mobile learning applications in early childhood education. *IGI Global*, 101–121. (2020).
45. Bhutoria, A. Personalized education and artificial intelligence in the United States, China, and India: A systematic review using a human-in-the-loop model. *Computers Education: Artif. Intell.* **3**, 100068 (2022).
46. Vanbecelaere, S. et al. Evaluating teachers' perceptions and use of a portal for digital personalised learning: a multiple case study in Flanders. *Educ. Inform. Technol.* **29**(3), 3389–3422 (2024).
47. Marougkas, A. et al. How personalized and effective is immersive virtual reality in education? A systematic literature review for the last decade. *Multimedia Tools Appl.* **83**(6), 18185–18233 (2024).
48. Kucirkova, N. & Leaton Gray, S. Beyond personalization: Embracing democratic learning within artificially intelligent systems. *Educational Theory* **73**(4), 469–489 (2023).
49. Na, W. E. I. et al. Human machine interaction-assisted smart educational system for rural children. *Comput. Electr. Eng.* **99**, 107812 (2022).
50. Han, Z., Tu, Y. & Huang, C. A framework for constructing a technology-enhanced education metaverse: Learner engagement with human–machine collaboration. *IEEE Trans. Learn. Technol.* **16**(6), 1179–1189 (2023).
51. Yousef, A. M. F. Augmented reality assisted learning achievement, motivation, and creativity for children of low-grade in primary school. *J. Comput. Assist. Learn.* **37**(4), 966–977 (2021).
52. Liu, Z., Dong, L. & Wu, C. Research on personalized recommendations for students' learning paths based on big data. *Int. J. Emerg. Technol. Learn. (iJET)* **15**(8), 40–56 (2020).
53. Tessema, W. M. & Cavus, N. Determining information system end-user satisfaction and continuance intension with a unified modeling approach. *Sci. Rep.* **14**(1), 6882 (2024).
54. Almaiah, M. A. & Alyoussef, I. Y. Analysis of the effect of course design, course content support, course assessment and instructor characteristics on the actual use of E-learning system. *Ieee Access.* **7**, 171907–171922 (2019).

## Author contributions

Mengru Li: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparationYang Lv: writing—review and editing, visualization, supervision, project administration, funding acquisitionYongming Pu: validation, formal analysis, investigation, resources Min Wu: writing—review and editing, visualization.

## Funding

## Declarations

## Competing interests

The authors declare no competing interests.

## Ethics approval

The studies involving human participants were reviewed and approved by Teachers' College, Chengdu University Ethics Committee (Approval Number: 2022.4059566). The participants provided their written informed consent to participate in this study. All methods were performed in accordance with relevant guidelines and regulations.

## Additional information

**Correspondence** and requests for materials should be addressed to Y.L.

**Reprints and permissions information** is available at www.nature.com/reprints.