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# Framework for adaptive multimodal serious games for early intervention of autistic children

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**Abstract: Background** Autism spectrum disorder (ASD) is a pervasive developmental disorder characterized by difficulties in social communication and restricted, repetitive behaviors. Early intervention is essential to improve developmental outcomes in children with ASD. Serious games, which combine educational objectives with game-based interactions, have shown potential as tools for early intervention in patients with ASD. However, in China, the development of serious games specifically designed for children with ASD remains in its infancy, with significant gaps in technical frameworks and effective data management methods. **Method** This paper proposes a framework aimed at facilitating the development of multimodal serious games designed for ASD interventions. We demonstrated the feasibility of the framework by developing and integrating several components, such as web applications, mobile games, and augmented reality games. These tools are interconnected to achieve data connectivity and management. Additionally, adaptive mechanics were employed within the framework to analyze real-time player data, which allowed the game difficulty to be dynamically adjusted and provide a personalized experience for each child. **Results** The framework successfully integrated various multimodal games, ensuring that real-time data management supported personalized game experiences. This approach ensured that the interventions remained appropriately challenging while still achievable. **Conclusion** The results indicate that the proposed framework enhances collaboration among therapists, parents, and developers while also improving the effectiveness of ASD interventions. By delivering personalized gameplay experiences that are both challenging and achievable, the framework offers a scalable platform for the future development of serious games.

**Keywords:** Autism spectrum disorder (ASD); Serious games; Multimodal games; Early intervention; Technical framework; Augmented reality (AR) Games; Mobile games

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## 1 Introduction

Autism spectrum disorder (ASD) is a pervasive neurodevelopmental condition characterized by restricted repetitive behaviors, interests, and activities, along with deficits in social communication and interaction [1]. With increasing diagnostic rates, public awareness, and changes in reproductive demographics, the prevalence of ASD has increased steadily in recent years. According to [2], the global prevalence of ASD is approximately 0.6%. The fifth edition of the 2024 publication of the Report on the Development of the Autism Education and Rehabilitation Industry in China [3] indicates that the prevalence of ASD in China ranges from 0.7% to 1.0%. The country is home to over 14 million individuals with ASD, with over 2 million children aged 0–14 years suffering from the disorder. However, there are no effective treatments to date because we still do not fully understand the causes of ASD, which vary greatly from person to person. Consequently, the field of special education has become increasingly interested in educational rehabilitation for patients with ASD.

Early intervention in ASD is primarily defined as the provision of therapeutic and educational services for children, particularly preschool-aged children with ASD. These services are designed to reduce the degree of developmental delay by assisting children in reaching their full social, emotional, physical, and cognitive potential, allowing them to enter the regular educational system or receive as little special education as possible, and to enhance the quality of family life and resilience of parents [3–5]. In 1982, Professor Guotai Tao first reported four cases of childhood autism [4], and since then, there have been some successes and experiences in educating children with ASD in China. However, ASD intervention and education in China are still in their infancy, with a lack of official and systematic guidance, an uneven development level of intervention, and the failure of all related industries to interact effectively. As a result, early intervention for ASD in China faces a major challenge: finding ways to use scientific and technological methods to improve the efficacy of early intervention and address issues related to distance and communication.

Serious games are a subset of video games that are not intended primarily for entertainment. Instead, they are designed as educational games that allow users to acquire information, training, or treatment during gameplay [7,8]. To facilitate the treatment of children with ASD, serious games have emerged as valuable instruments that concentrate on the development of social, communicative, and emotional skills [9–11]. Games with multimodal interfaces, whether augmented reality (AR), computer games, or mobile applications, have demonstrated efficacy in enhancing social cognition, including emotion recognition, in children with autism [10]. The assessment and creation of serious games are significantly affected by multimodal interfaces that allow for a detailed review of thinking skills, emotional states, and how players interact with games [11].

Although serious games have been extensively employed in interventions for children with ASD, a limited number of serious games are specifically designed for children with ASD in China, and they are still in the early phases of development [14, 15]. Additionally, most serious games for children with ASD are self-contained and lack advanced technical support frameworks, effective administration and analysis of player data, and game optimization based on useful information.

To resolve these concerns, we analyzed numerous models, architectures, and existing serious game technologies. This study introduces innovations in the following areas.

- We created a novel technological framework to facilitate the development of multimodal games designed specifically for children with ASD. This framework facilitates the following.
    - We provide unified data management across games and web applications.
    - APIs facilitate data sharing and optimization.
- The framework facilitated the successful implementation of web applications and multimodal games,

such as:

- A mobile game.
- An augmented reality (AR) game.

• The introduction of adaptive mechanisms within games substantially contributes to their optimization.

Although the focus of our work is on the design and architecture of this technological framework, concrete game implementations and optimization methods are presented in later sections to demonstrate their application and validation.

## 2 Related work

This section explores the literature on serious games specifically designed for children with autism, including mobile and AR games, and existing technological frameworks and platforms.

### 2.1 Serious games

In recent years, researchers have investigated the potential of serious games as a therapeutic instrument for individuals with ASD. For example, Tsikinas and Xinogalos [7] conducted a literature review and determined that most studies on the impact of serious games on individuals diagnosed with ASD or intellectual disabilities yielded favorable results. Similarly, a literature review conducted by Hassan et al. [11] concluded that the use of serious games yielded favorable outcomes, particularly in the improvement of social and socio-emotional abilities. Educational games have the potential to enhance the social skills of children by providing them with an opportunity to learn about the world in which they reside [16,17].

Seven components were identified by Whyte et al. [16] for the design of serious games for children with ASD to maintain student motivation while playing the game, as the skills to be acquired may be challenging and require a significant amount of time (up to weeks or months). Drawn from two separate sources [19,20], these components consist of individualized training and choice, increasing levels of difficulty, game stories, objectives, rewards, and feedback.

These game design theories have assisted in the development of numerous meaningful games for children with ASD. The following categories of games can be classified based on their purpose: edutainment, game-based learning, simulation games, games for health, exergaming, art games, productivity gaming, gamification, and advergames [19]. Based on various interactive interfaces [20], games can be classified into computer games, mobile games, XR games, Kinect games, and other games that utilize special interactive devices such as robots [21] and wearable devices [22].

Researchers can acquire and analyze data from various sources, including sensors, log data, and in-game metrics, using various interactive interfaces. This information provides helpful details about the user's experience and engagement [23]. Oviatt asserts that multimodal interfaces have the "potential to greatly expand the accessibility of computing to diverse and nonspecialist users and to promote new forms of computing not previously available" [22]. The primary advantage for users is their ability to transition between various forms of mixed reality environments and complete a variety of tasks. Various interface techniques can be implemented to enhance the appeal of the user experience during exploration. The incorporation of multimodal interfaces into serious games improves evaluation processes and contributes to the development of inclusive and engaging user experiences.

### 2.2 Mobile games

Mobile applications designed for children with ASD have shown significant potential in autism care, diagnosis, and intervention [24]. Mobile games are the most prevalent mobile applications, particularly for

children with ASD, to enhance their communication and social interaction skills. MOSOCO [25] is a mobile assistive tool designed to help children with autism improve their social skills through real-life practices in outdoor environments and by blending digital guidance with real-world interactions. The study [26] focuses on the design and evaluation of mobile learning applications tailored to children with autism in Pakistan, emphasizing localized content and user feedback to improve engagement and learning outcomes. An augmentative system [27] was developed to integrate facial and emotion recognition technologies to enhance the social skills of children with ASD, particularly in recognizing and responding to emotions. A method [28] was proposed to develop accessible serious mobile games specifically designed for children with ASD, focusing on usability and accessibility to enhance social and cognitive skills through interactive play. Autisay [29] is a mobile communication tool designed for individuals with autism to facilitate social interactions and address communication barriers through user-friendly interfaces. The use of an app embedded with video [30] is modeled to increase eye contact among individuals with autism, demonstrating significant improvements in this key social behavior.

Mobile games enhance independent living skills and behavioral improvements in children with ASD. PlanTEA [31] is a mobile app designed to help children with ASD prepare for medical appointments and improve their anticipation and planning through visual aids and task structuring. A mobile app that uses augmentative and alternative communication (AAC) and video modeling [32] was developed to assist children with autism in learning. Fage et al. [33] presented the design and evaluation of an emotion regulation application aimed at supporting the inclusion of children with ASD in school environments by focusing on emotion recognition and coping strategies.

In addition, mobile games are intended to enhance students' general learning abilities. A web app [34] is designed with visual aids to help children with ASD learn piano, using technology to create more accessible music education for students with special needs. Ntalindwa et al. [35] described the development and usability testing of a mobile app created to improve numeracy skills in children with ASD, utilizing a participatory design to ensure user-friendliness. An et al. [36] developed and evaluated a speech-generating AAC application aimed at supporting minimally verbal children with ASD in China by focusing on communication development and usability in a local context. BIUTIS [37] is a mobile application designed as a learning aid for children with autism to improve their language acquisition skills. The Fill Me App [38] is an interactive mobile game designed to engage children with autism through play, with the aim of developing cognitive and motor skills. DoBrain [39], a mobile-based cognitive training program, was evaluated in a randomized trial for its usefulness in enhancing the cognitive function of preschool children with and without developmental problems.

Mobile games promote physical activity, which is crucial for children with ASD. One study demonstrated positive outcomes of using outdoor games tailored to this demographic [40]. As illustrated in [41], the mobile game model for children with autism allows teachers to monitor and evaluate pupil performance through a web application.

Yuudee [36], one of the few mobile games that have been professionally designed and developed specifically for children with ASD in China, was effective in enhancing the request skills of these minimally verbal children.

### 2.3 Augmented reality (AR) games

AR has undergone significant transformation as a novel form of human-computer interaction (HCI) technology. It integrates real-world and virtual data to deliver a wide range of interactive experiences and detailed visual information [42]. Research indicates that individuals with autism are enthusiastic about utilizing digital devices and processing visual information, and AR offers novel concepts to enhance their

educational experience [43].

Studies [44] on using AR technology to facilitate the learning of children and adolescents with ASD were reviewed. Research has shown that mobile apps can significantly improve thinking skills, social interactions, and speech abilities through fun activities that use AR features and visual hints [45]. Various skills, including attention management, navigation, facial expressions and emotions, literacy, social communication, and tooth flossing, were taught to individuals through mobile applications that included AR elements [46]. In particular, AR games make the treatment process more engaging [49, 50], enhance the learning abilities of children with ASD, and positively impact their academic performance [51–54].

The AR studies examined focused primarily on social skills, which are the most obvious deficiency in children with ASD. With AR, training can be conducted in a safe, regulated, and customizable environment by incorporating a combination of real-world and virtual elements to simulate a social environment [46]. The characteristics of this intervention are particularly compelling in the context of ASD treatment. These studies [50, 53, 55, 56] observed significant improvements in emotional intelligence and social-emotional reciprocity.

### 2.4 Technological frameworks

Technical support frameworks are essential for professional games. It is evident that the development of a technology framework for multimodal serious games has gained momentum in various fields, particularly cognitive rehabilitation [57–60] and education, despite limited academic literature on the subject. κPAX [59] is a technological framework for serious games that offers a system of pluggable modules, gamification, and social network integration for improving the learning experience through feedback and engagement mechanisms. PlayWithUnicam [60] is an extensible platform for serious games. It provides free access, content customization, and multiplayer support, making it suitable for multimodal serious games. StoryPlay Multimodal [61] is a mobile platform specifically designed for analyzing serious games. It can capture, synchronize, and visualize multimodal data to remotely and asynchronously evaluate the design of serious games.

There is a lack of research on technology platforms associated with games designed for specific populations. Ludo Minga [62], a technological platform, offers an inclusive and accessible environment for serious activities specifically tailored to individuals with intellectual disabilities. The platform enhances learning through interactive and engaging experiences. The technological platform [41] was designed to provide comprehensive treatment for children with ASD, with particular emphasis on the use of serious games for emotional and social learning therapy.

## 3 Methods

In this study, we devised and implemented an exhaustive technological framework that encompasses multimodal serious games for children with autism and corresponding technical support for various users. The framework architecture is introduced first, followed by a detailed description of the methods devised and designed for children with ASD. It includes a game design framework and workflow.

### 3.1 Framework architecture

The framework is primarily divided into three modules: web applications, data storage, and multimodal games, as illustrated in Figure 1. Although multimodal games vary, the data generated during gameplay are stored in the cloud in real time via a unified interface. The integration of mobile- and AR-based games in the proposed framework is motivated by their complementary strengths in supporting early interventions for

children with ASD. Mobile games provide a familiar and easily accessible format for cognitive skill development and are often used in home or therapy settings. By contrast, AR games enhance situational awareness and real-world interaction, making them particularly suitable for training social or spatial skills. Although the same learning goal may be implemented in both environments (e.g., object recognition or matching), the immersive AR interface offers different sensory engagements, allowing therapists to compare children's performances in 2D and 3D spatial contexts. By incorporating both modalities, the system ensures diversity in the therapeutic experience while supporting cross-scenario adaptability and comparison.

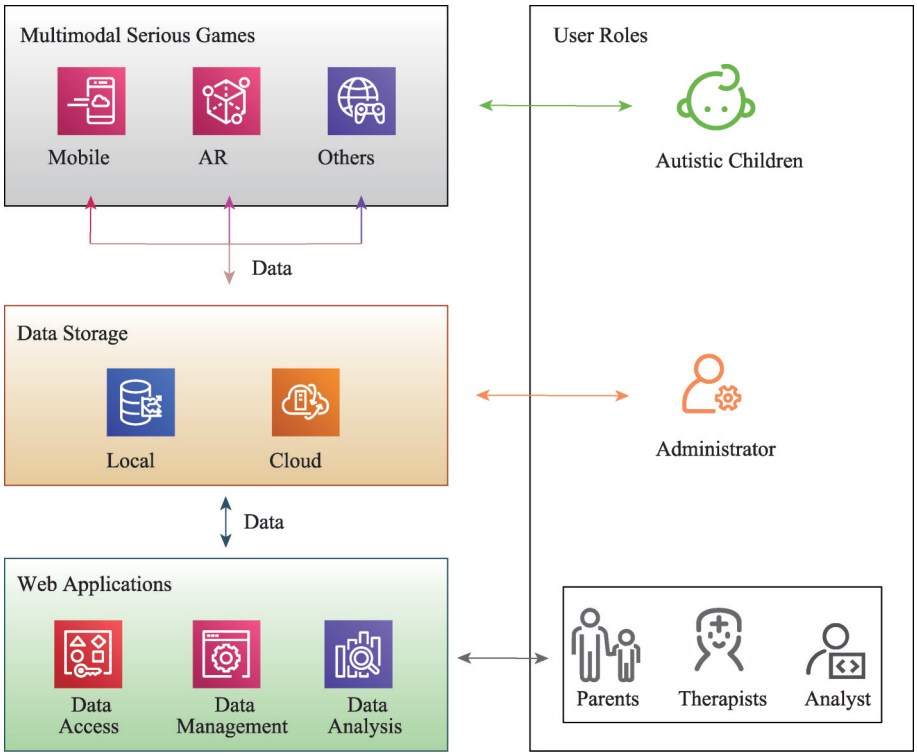



**Figure 1** Framework architecture diagram.

Web applications provide a range of data access, administration, and analysis functions for various user roles on a website. As shown on the right-hand side of Figure 1, the roles requiring authentication include administrators, data analysts, therapists, and parents. The platform allows parent users to access the associated child's information, game progress data, and therapy record data, among other things, for the purpose of self-assessment. The therapist's role is primarily intended for certified therapists or teachers to manage the therapeutic records of the associated therapeutic subjects and observe their game progress data. The analyst is responsible for constructing the game optimization models and data analysis. The administrator is primarily responsible for managing the fundamental information, including basic user data and game recordings.

In addition to the functional architecture shown in Figure 1, the system incorporates a unified data flow design that manages the information exchange between games and web applications. All roles—administrators, therapists, parents, and analysts—interact with centralized data sources via authenticated access. Game clients and web platforms feed user activity and therapy records into cloud-based storage, whereas data management services provide content administration and analytical tools tailored to each role. Identity verification and access control are consistently enforced across both application types to ensure secure role-specific data handling.

### 3.2 Game design framework

It is imperative to develop a gamification framework for children with autism that incorporates therapeutic elements to improve their interaction skills in mobile games, with particular emphasis on motivation and engagement within therapeutic procedures [63]. A comprehensive gamification framework [64] was created to facilitate the development of interaction skills in children with autism. The proposed gamification framework is validated by obtaining expert feedback and a gamification prototype at the conclusion of the research phase [64]. Our game design framework utilized the guidelines established in this study [65], which were subsequently implemented in over 55 additional systems designed for children with ASD.

We designed our game framework to accommodate multimodal games and have already achieved unified support for both mobile and AR games. The primary objective of integrating serious games into this system is to enhance the cognitive abilities and independent living skills of children with ASD. The primary applications of mobile games and AR games are home education and intervention therapy for children with ASD, as well as supplementary teaching in educational institutions, owing to the convenience of mobile devices serving as game terminals.

This study establishes a unified design concept for games despite their development using distinct technologies, as illustrated in Figure 2. To accommodate the unique therapeutic requirements of children with autism, the reward mechanism of the games was developed with customizable reinforcements, and guidance and cooperation were implemented despite the diverse types and contents of the games. Data were collected in real time during the game and aggregated on an online management platform for analysis. The game also incorporates an adaptive mechanism that first transfers the game data to an evaluation model to assess the effectiveness of the intervention. The results of the evaluation are then fed back into the game to adaptively adjust the game content, including the game scene, achievements, feedback, levels, and rules, to achieve better intervention.

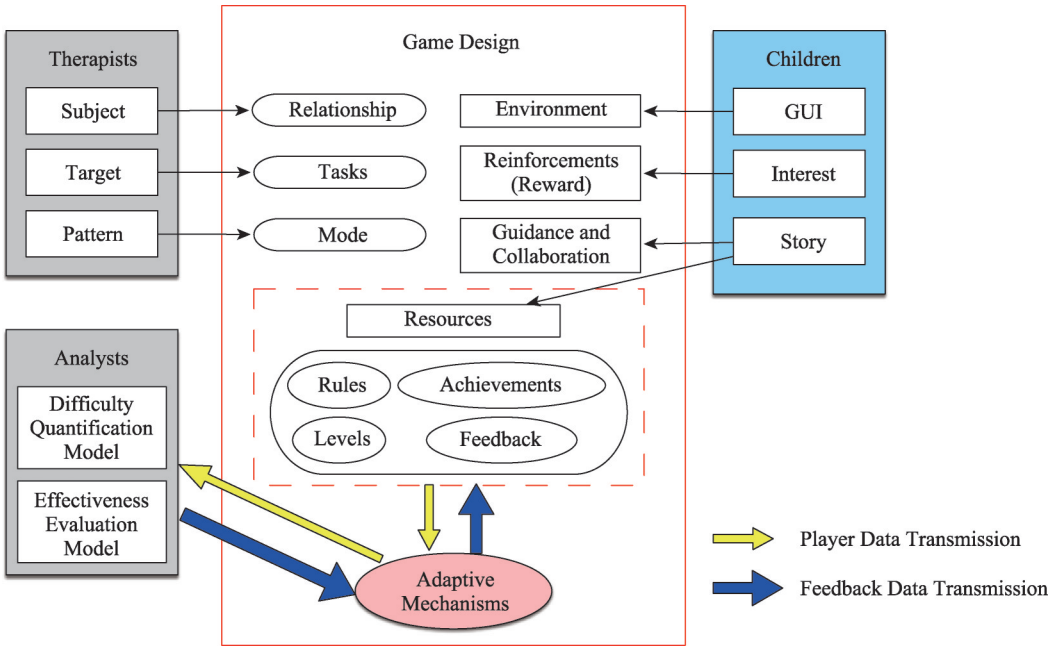



**Figure 2** Game design framework. Graphical user interface (GUI) elements are used in the game design framework to support interaction.

### 3.3 Game workflow

Based on the proposed framework, each game category was independently designed and developed using

Unity [66], following a consistent workflow. After logging in via mobile number, email, or social media (e.g., WeChat, QQ), users access the main interface, where they can select game types, view tutorials, or review progress reports. Web-based data management systems handle authentication and synchronize user data across platforms.

During gameplay, players attempt to complete progressively challenging tasks. Successful task completion, such as selecting the correct object within a given time or accuracy threshold, triggers the reinforcement module to provide immediate feedback. Reinforcements are categorized into three types: audio, video, and picture, each customizable according to the child's preferences. For example, audio rewards consist of prerecorded messages from parents or therapists uploaded via a platform or recorded using built-in tools. Video and image rewards may include cartoons, animal photos, or family scenes uploaded by caregivers. The system automatically selects and provides appropriate reinforcement based on the task outcome and game context. When specific content is unavailable, fallback defaults are used to ensure a seamless experience. This reinforcement mechanism balances personalization with usability, maintaining motivation and emotional engagement without overburdening caregivers.

The framework also has standard ways to connect different types of games, allowing for consistent data collection (e.g., category, difficulty, time spent, and achievement value) and making it easier to add new game types in the future.

## 4 Implementation

To comprehensively assess the feasibility of the technology framework for this study, we developed websites that provide data management for users in various roles as well as distinct categories of multimodal serious games. A single interface and a method for sharing data can be used to offer support services for more types of serious games, as shown by the two game prototypes that follow the design framework mentioned earlier.

### 4.1 Web applications

The web applications developed in this study can be divided into two components: the first component is a website for the general public, which includes scientific information about ASD; an introduction to the games (Figure 3(a)); self-tests on ASD (Figure 3(b)); and user information. The second component is a web-based shared data management platform for serious games and websites that offers a unified authentication service, data management, and analysis service for four types of roles (see Figure 1): administrators, data analysts, therapists, and parents. The second component primarily consists of two functional modules: data management and data analysis, with different roles granting varying privileges within these modules.

Parents have the privilege of modifying personal information and viewing shared game information, therapist information, intervention logs, and game logs for their children when they access the data management module. Conversely, when parents enter the data analysis module, they have the privilege of accessing the assessment scale records of their children.

The role of therapists is predominantly that of certified therapists and educators. Upon entering the data management module, this role is granted access to the game records of its respective clients and shared game information, as shown in Figure 3(c). In addition, they have the privilege to alter their personal information and add, delete, or modify intervention records.

The primary responsibility of the analyst is to construct an assessment scale model and analyze and process the data. The analyst can modify personal information and view shared game information upon entering the data management module. This role has the ability to add, delete, and modify the assessment

scale model; build and modify the optimization model of the games (Figure 3(d)); and alter the content of the game learning report generation when they enter the data analysis module.

The administrator's primary responsibility is to manage fundamental information, including users, activities, and logs. This role has the privilege of adding, deleting, and modifying game information, organization information, user information, and game records, as well as updating personal information when entering the data management module. The assessment scale and game learning models are visible when entering the data analysis module.

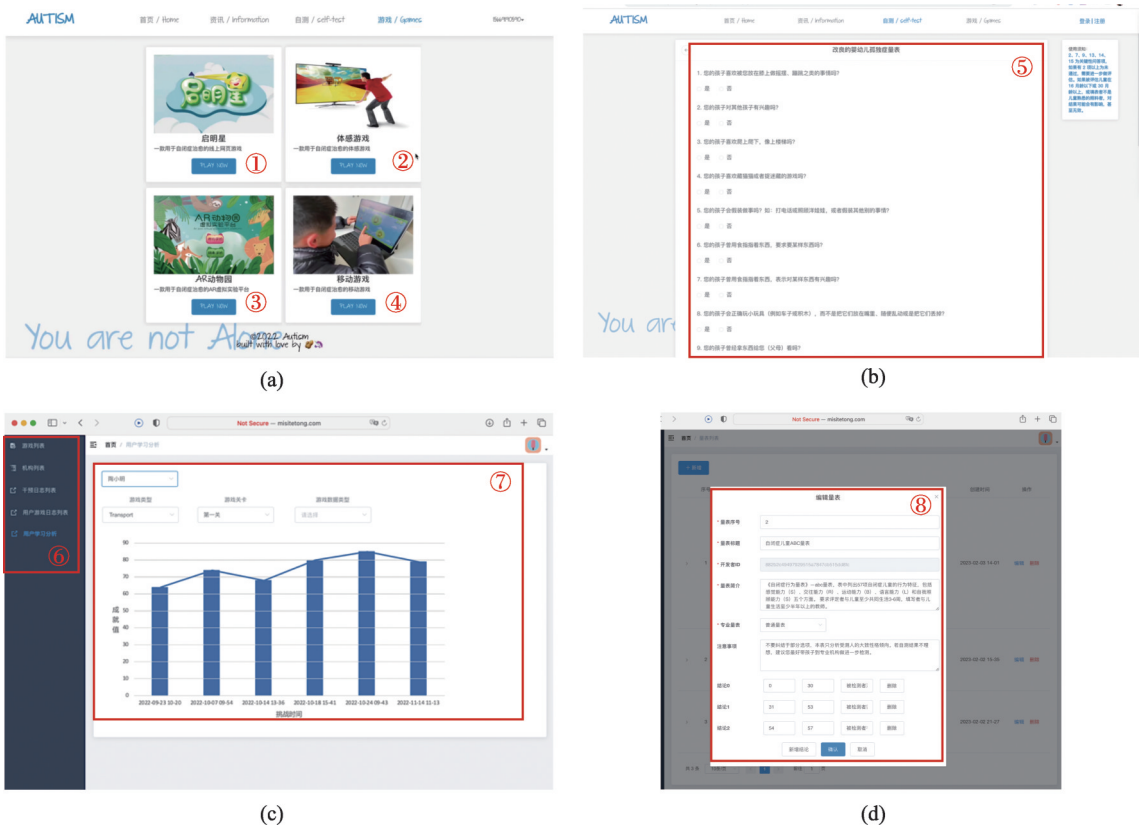



**Figure 3** The web applications: (a) provides the introduction page to the various types of games included in the system: ① a web-based game, ② a motion-sensing game, ③ an augmented reality (AR) game, and ④ a mobile game; (b) displays the interface of the M-CHAT screening page, ⑤ indicates the test content presented in a single-choice format; (c) displays the therapist interface page, where ⑥ represents the various functions available to the therapist role, and ⑦ shows a bar-line chart illustrating changes in user achievement values over time; (d) displays a section of the analyst interface, in which ⑧ illustrates the content involved in constructing the assessment scale model.

### 4.2 Multimodal serious games

A simplified game design document (GDD) guided the development of both mobile and AR games. Each game was designed as a single-player experience, targeting children aged 3 – 10 years with ASD, and gameplay was optimized for mobile touchscreen devices, AR-compatible tablets, or smartphones. The games adopt short, focused interaction loops with clearly defined goals and adaptive difficulties. The design prioritizes accessibility, reinforcement feedback, and data tracking, aligned with therapeutic use cases. Environmental factors, including distraction minimization, visual clarity, and interface simplicity, were also considered to ensure suitability for the target population.

#### 4.2.1 Mobile game

We created a mobile game using Unity that focuses primarily on cognitive development and encompasses

fundamental components of life, including numbers, shapes, colors, animals, and transportation methods.

The learning process is structured as follows: Initially, the child player must select and enter a specific category of game, such as the color game, as illustrated in Figure 4(a). The child player must then choose whether to enter the level, as shown in Figure 4(b). The goal is displayed in the upper half of the game interface, and the child player must select a pattern that is consistent with or matches the goal from multiple options that appear on the lower half of the screen, as illustrated in Figure 4(c). Upon making the correct choice, the child player successfully passes the level, receives feedback from the reinforcement, and chooses to either replay it or advance to the next level, as illustrated in Figure 4(d). The game background utilizes log files to autonomously record data such as clearance time and correct rate. This data is then transmitted to the adaptive adjustment mechanism, which is elaborated on in the subsequent section.


**Figure 4** The mobile game: (a) category selection interface, where ① represents number games, ② represents traffic games, and ③ represents shape games; (b) level selection; (c) cognitive matching training; (d) success screen, in which ④ highlights the customizable reinforcement.

In the mobile game, when the player selects an incorrect option or fails to complete a level within the required time or accuracy threshold, gentle reinforcement is provided. The system offers the child the option of retrying the same level or returning to the main menu. Regardless of the outcome, the performance data is recorded and sent to the adaptive adjustment module to inform future difficulty tuning. This approach avoids a punitive design and encourages persistence while respecting the emotional needs of children with ASD.

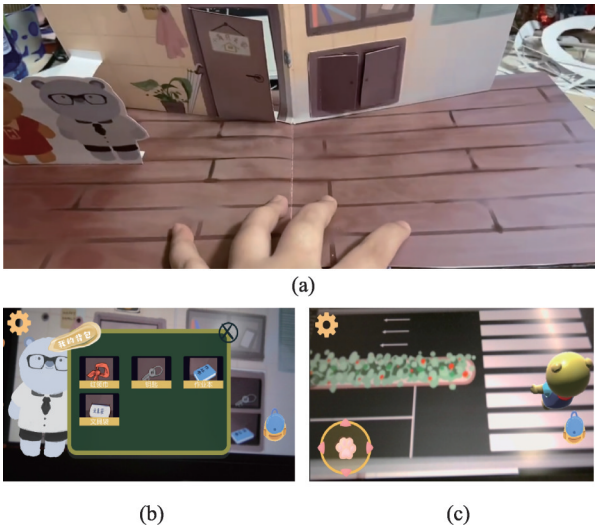
#### 4.2.2 AR game

An AR game for autistic children with specific reading abilities was developed using Unity and Vuforia [67] in accordance with the game design framework and methodology outlined in subsections 3.2 and 3.3. The game utilizes AR technology and a three-dimensional picture book to integrate virtual information with real-world scenarios, thereby enhancing the players' perceptions of immersion. In this AR game, the player assumes the role of a student at a special school in Shanghai, "Little Hai Bei", and integrates the game with the 3D picture book "One Day Routine" to complete the daily life skills training required to be mastered during the schooling process. This training includes the acquisition of knowledge of daily necessities and traffic safety.

The book “One Day Routine” consists of ten pages, and every two pages is a three-dimensional book scene that corresponds to a game level, as illustrated in Figure 5(a). Therefore, the game comprises five levels, each of which corresponds to one of the following five scenarios: leaving home, safely traversing the road, navigating traffic lights, interacting with classmates, or interacting with instructors. To advance the narrative, players must use a mobile device with a camera function to capture images of the picture book, identify the images within the book, and complete the corresponding content at that level. The first level of the scene, “leaving home”, necessitates that the user drags and drop all necessary items into their backpack to complete the level task, as illustrated in Figure 5(b). The second level, “on the road,” requires the user to click on safe walking paths, including sidewalks and zebra crossings. In the third level, the player encounters a traffic light. To cross the zebra crossing, the player must long-press the forward direction in the lower left corner when the light is green, as illustrated in Figure 5(c). Otherwise, the prompt fails. The player encounters classmates and instructors at school on the fourth and fifth levels. The game guides players through dialogue, allowing them to select an appropriate salutation phrase for the scene by clicking on various options. In addition, the game offers a recording function that allows players to upload phrases for playback and selection.

The objective of the game is to enhance the cognitive abilities of children with autism by providing them with enjoyable gameplay that emphasizes fundamental daily life skills. Users can customize the reinforcements in the game that they receive after successfully completing a level. Data, including the player’s clearance time and correct rate, is automatically recorded by the system and transmitted to an adaptive mechanism via a log file.

In the AR game, if the child is unable to complete a task correctly, the system does not enforce a strict retry but instead provides non-intrusive redirection to proceed to a simplified task. Visual and voice guidance encourages further engagement. The intention was to reduce cognitive load and maintain immersion without introducing frustration. Data from unsuccessful interactions are logged for evaluation purposes, and repeated failures in similar contexts can trigger a reduction in task complexity through adaptive mechanisms.



(a)

(b) (c)

**Figure 5** The AR Game: (a) 3D illustrated book; (b) Scene “Leaving Home”; (c) Scene “With Traffic Lights”.

### 4.2.3 Adaptive mechanism

Dynamic difficulty adjustment (DDA) is a real-time process that automatically modifies a game’s behavior, features, and scenarios according to the player’s skill level [68]. Serious games apply DDA to maintain

players' interest and involvement in the learning process [69]. However, the task of DDA is complex because it must accurately predict the next entry into the game in real time at an appropriate moment [70].

To monitor and assess the learning effects of serious games on children, this study continuously monitored two critical data points in game logs: the number of interactions and the time required to complete each level. A pertinent mathematical model was designed to develop the concept of achievement value on this basis. This study assumed that users learn more effectively when their achievement value is high.

The subsequent section provides a comprehensive introduction to achievement value from two distinct perspectives: level achievement value and category achievement value.

(1) Level achievement value

This study first constructs relevant mathematical models for evaluating the clearance time of passing the level and the accuracy rate to calculate the level achievement value, assuming that the current game category is $A$ and the achievement value labeled as the current game level is $A(i)$.

• Evaluation of clearance time

For level $i$, the clearance time is evaluated, denoted as $\theta(i)$ in this study, and four key parameters are designed, with their corresponding meanings, as illustrated in Table 1.

**Table 1** List of key parameters for $\theta(i)$

| Parameter | Meaning |
|---|---|
| $s_i$ | Value of ranking stars for that level, in general, $s_i \geq 3$ |
| $wt_i$ | Level's time weighting, which varies according to the difficulty of the level |
| $t_i$ | Theoretical time required to finish the level. This duration will be dynamically and linearly adjusted in accordance with the time spent by all participants. |
| $\Delta t$ | Total amount of time this player has spent on the level |

The theoretical time $t_i$ serves as a baseline reference for comparing actual task completion times under controlled conditions. This reflects the average expected time that a typically developing child might take to complete a given task without distraction or difficulty. This enables us to evaluate whether a child with ASD is performing within, above, or below the expected range, facilitating adaptation to game difficulty accordingly.

The time-weighting factor $wt_i$ is used to adjust the impact of time performance on the overall assessment score. It is calibrated based on pilot tests and therapist feedback and can be tuned to emphasize speed, accuracy, or both, depending on the therapeutic goal (e.g., stress reduction vs. cognitive training).

The clearance time evaluation $\theta(i)$ is determined as eq. (1).

$$\theta(i)=\begin{cases}\left(s_i-\left\lceil\dfrac{\Delta t}{t_i}\right\rceil\right)\times wt_i, & \Delta t\in\left[0,\ s_i\times t_i\right],\\ 0, & \Delta t>s_i\times t_i.\end{cases} \tag{1}$$

• Evaluation of accuracy

The accuracy of the $i$ th level is denoted as $C(i)$. Accuracy, in this context, refers to the proportion of correct responses a child provides during gameplay. For mobile games, this includes correctly identifying target items (e.g., matching shapes, colors, or numbers). AR games include correct physical interactions or successful completion of environment-based prompts.

The accuracy was evaluated based on the four core parameters presented in Table 2. In this framework, the fault tolerance refers to the maximum number of incorrect attempts allowed before a player is required to repeat a level or receive guidance. It is defined as a threshold parameter that balances flexibility and challenges in gameplay. The fault tolerance value is typically determined through consultation with a

therapist and pilot user testing. A lower value results in quicker reinforcement of correct behaviors by limiting tolerance to repeated errors, which is useful in cognitive training phases. Higher fault tolerance accommodates children with greater variability in responses, offering more freedom before corrective actions are triggered. Adjusting this parameter allowed therapists to personalize the gameplay experience based on each child's attention span, frustration tolerance, and learning pace.

**Table 2** List of key parameters for $C(i)$

| Parameter | Meaning |
|---|---|
| $e_i$ | Incorrect number of attempts |
| $cl_i$ | Total number of attempts |
| $ec_i$ | Fault tolerance |
| $wc_i$ | Accuracy weighting of the level, which is contingent upon its level of difficulty |

The computational model for accuracy evaluation $C(i)$ is shown in eq. (2). This metric is essential for assessing a child's understanding of task content and informing the adaptive adjustment of difficulty levels.

$$C(i)=\begin{cases}\left(1-\dfrac{e_i}{cl_i}\right)\times wc_i, & e_i<ec_i,\\ 0, & e_i\geq ec_i.\end{cases} \tag{2}$$

This study ultimately establishes the achievement value $A(i)$ by integrating the clearance time $\theta(i)$ and accuracy $C(i)$ as eq. (3).

$$A(i)=\frac{\theta(i)+C(i)}{2}. \tag{3}$$

(2) Category achievement value

The category achievement value is the average of the achievement values for all levels within that category. Given that the current game category is $A$ and there are $k$ levels with achievement values, each of which is denoted as $A(i)$, the total achievement value for the category can be denoted as eq. (4).

$$A=\frac{\sum_{i=1}^{k}A(i)}{k}. \tag{4}$$

(3) Adaptive adjustment model

This study endeavors to incorporate an adaptive adjustment model into the game's difficulty design to comprehensively analyze and improve the learning effects on participants. To more clearly articulate the mechanism's design, this study will employ the symbols $i$ to denote the $i$th level and $i+1$ to denote the $(i+1)$ th level. This is predicated on the assumption that the antecedent sequence has already attempted the $(i+1)$ th level $k$ times and that both $i$ and $k$ are greater than 0. The meanings of the other four key parameters incorporated in the model are illustrated in Table 3.

**Table 3** List of key parameters in adaptive adjustment model

| Parameter | Meaning |
|---|---|
| $A_k(i+1)$ | Achievement value of the most recent breakthrough on level $i$+1 |
| $ec_i$ | Fault tolerance of the $i$-th level |
| $ec_{i+1}$ | Fault tolerance of the $(i+1)$ th level |
| $\sigma_{k+1}$ | Parameter for the $(k+1)$ th break-in adjustment |

The current design concept of this model is to predict and modify the fault tolerance of the subsequent level based on the fault tolerance of the current level $ec_i$ and adaptively regulate the fault tolerance of the next level $ec_{i+1}$. In the initial stage, the baseline fault tolerance was inferred from the aggregated

accomplishment data of previous participants to personalize the starting difficulty.

Therefore, eq. (5) defines the adaptive adjustment model developed in this study.

$$ec_{i+1} = ec_i \times \frac{A_k(i+1) \times k}{\sum_{j=1}^{k} A_j(i+1)} + \sigma_{k+1}. \tag{5}$$

To address incorrect attempts, the adaptive mechanism incorporates several nonpunitive strategies to support gradual learning.

• **Repetition of the current task with enhanced prompts or guidance** helps players better understand the required skills.

• **Delaying level progression until a predefined success threshold is met** ensures skill consolidation prior to advancement.

• **Reducing the achievement value for the current task to reflect reduced performance**, which, in turn, influences reward feedback and progression tracking.

• **Dynamically adjusting the fault tolerance of the subsequent level** $ec_{i+1}$ based on the performance at the current level $ec_i$, as determined by eq. (5). Higher success leads to lower fault tolerance and increased difficulty, whereas repeated failures result in easier tasks. Therapists may also intervene by adjusting a dynamic parameter $\sigma_{k+1}$ for personalized support.

These mechanisms ensure that game difficulty adapts to the player's demonstrated skill level, maintaining motivation while preventing cognitive overload. Rather than punishing mistakes, the system focuses on supporting gradual improvement through responsive and personalized gameplay experiences.

## 5 Discussion

The proposed framework effectively supports two multimodal serious game prototypes developed by two distinct experienced development teams. The two teams reached a consensus on the framework design: a unified data storage and management system and a unified data interface for various game types. We conducted discussions and analyses from two perspectives, namely, therapists and parents, to further validate the efficacy of this technical framework. The rehabilitation institution in Hangzhou, China, which specializes in providing services to children with autism, was the source of volunteers participating in this discussion, which included therapists and parents.

### 5.1 Therapists

We invited five professional therapists to utilize a web-based data storage and management platform and presented them with two games to play. We then presented them with four questions and requested them to anonymously select one of the following responses on a five-point Likert scale: Strongly disagree, Disagree, Neither agree nor disagree, Agree, or Strongly agree.

• Question 1: Will you support the design of a technological framework that involves the unified storage and management of target recipients' data to facilitate tracking and analysis of treatment effects?

• Question 2: Will you consider employing the web applications in your future projects?

• Question 3: Do you agree that serious games are beneficial for individuals with ASD?

• Question 4: Will you suggest that your clients play our serious games?

Table 4 presents the responses to the four questions. As shown in Table 4 and Figure 6, the choices made by the therapists suggest that they believe technology platforms are important for storing and managing data in everyday treatment and that serious games can positively affect interventions. However, they were also apprehensive about the security of data, the potential increase in their workload due to the operation of the learning platform and games, the potential for an excessive number of game types to create a learning and

**Table 4** Therapists' responses to the four inquiries

| | Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree |
|---|---|---|---|---|---|
| Question 1 | | | 1 | 2 | 2 |
| Question 2 | | 1 | 2 | 2 | |
| Question 3 | | | 1 | 2 | 2 |
| Question 4 | | | 1 | 3 | 1 |

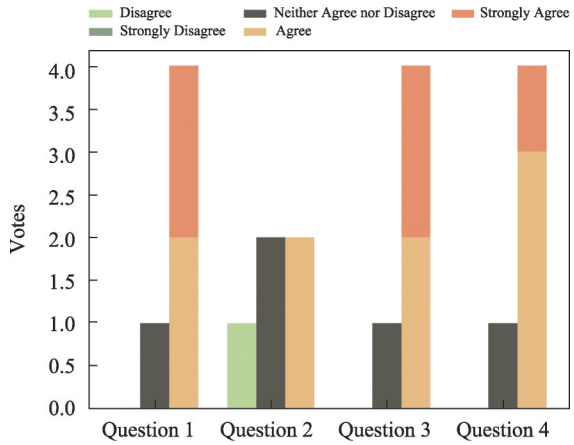



**Figure 6** Visualization of table 4. The bar representing strongly agree is stacked with the bar for agree, while the bar for strongly disagree is stacked with the bar for disagree

treatment burden for children, and the potential for children to become overly dependent on electronic devices rather than developing social skills.

During the pilot-testing phase, the therapists provided qualitative feedback based on their professional experiences and observations. They noted that children responded more positively when reinforcement was timely and difficulty levels were adapted accordingly. Strict fault tolerance settings tend to cause frustration, whereas overly lenient settings encourage guessing behaviors. The adaptive model, especially fault-tolerance-based regulation, was viewed as promising for balancing challenge and motivation. However, our findings are preliminary. Further empirical testing with actual users is required to refine the parameter settings, validate adaptive strategies, and optimize the model for broader deployment.

### 5.2 Parents

Our web applications and activities were initially accessible to ten parents who were invited to participate as users. They were prompted to respond to four queries anonymously on a five-point Likert scale.

• Question 1: Would you like to use web applications to monitor and analyze treatment outcome data for your children?

• Question 2: Do you agree that serious games can be a beneficial intervention for children with ASD?

• Question 3: Are you willing to allow children to remain unsupervised while using mobile and AR games for therapy?

• Question 4: Would you like to play serious games for therapy under the guidance and supervision of a therapist?

Table 5 lists the four queries selected by the parents. Only nine parents responded to Question 4, and one parent chose not to answer this item. As illustrated in Figure 7, most parents expressed favorable sentiments regarding the technological framework. However, parents remain uncertain about the positive effects of serious games on interventions. Additionally, most parents criticized their children's independent play in the game. They also expressed concerns that web applications are not as user-friendly as mobile applets or

**Table 5** Parents' responses to these four enquiries

| | Strongly disagree | Disagree | Neither agree nor disagree | Agree | Strongly agree |
|---|---|---|---|---|---|
| Question 1 | | | 3 | 5 | 2 |
| Question 2 | | 2 | 4 | 3 | 1 |
| Question 3 | | 2 | 5 | 3 | |
| Question 4 | | | 1 | 6 | 2 |

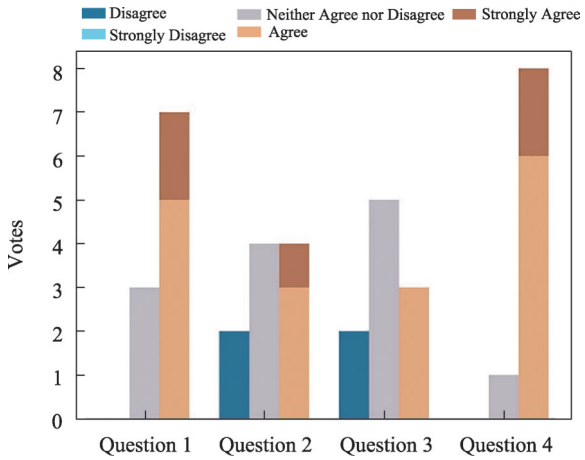



**Figure 7** Visualization of table 5. The bar representing strongly agree is stacked with the bar for agree, while the bar for strongly disagree is stacked with the bar for disagree.

mobile apps, they are concerned about data security, and they worry that children will develop an addiction to playing video games. However, they preferred to participate in game intervention therapy under the supervision of a professional.

## 6 Conclusions

The proposed framework provides technologically unified data storage and management for multimodal serious games, thereby simplifying the process of viewing and managing game progress and providing therapeutic data for users. This framework also has standardized interfaces for multimodal games, enabling the seamless integration and expansion of additional games. The framework's ability to accommodate a wide range of games and the unified data management that underlies them is illustrated by the successful deployment of two serious game prototypes: one mobile and the other AR-based.

Furthermore, the investigation of adaptive mechanisms has significantly enhanced the quality of game content for children with ASD. The framework ensures that the game matches the player's evolving skill level by adjusting the game's difficulty and feedback through real-time monitoring and data analysis. This is corroborated by real-time data collected during gameplay, which automatically assesses performance and adjusts the difficulty level to enhance the effectiveness of the intervention. The potential of serious games as beneficial intervention tools for children with autism, particularly in enhancing their cognitive and social-emotional abilities, has been underscored by both therapists and developers who have provided positive feedback.

Future research could focus on improving the adaptive adjustment mechanism, boosting data security, and gathering user data to allow for better analysis when permitted. This would lay the groundwork for adding reinforcement learning methods to future treatments, which would improve the therapeutic benefits of these games in children with ASD.

## Declaration of competing interest

We declare that there are no competing interests.

## CRediT authorship contributions statement

**Zhiqi Xu:** Conceptualization, system design, formal analysis, investigation, resources, visualization, and writing of the original draft. **Yuyong Zhao:** Implementation of the web system, data collection and formal analysis. **Jie Wang:** Design and development of games, data collection and resources. **Jian Chang:** Review and editing. **Yuetian Zhang:** Resources, visualization and validation.

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