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Development and usability evaluation of an adaptive cognitive training game based on raven's coloured progressive matrices

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ABSTRACT

This study proposes an intelligent adaptive cognitive training system based on a soft computing approach to enhance non-verbal reasoning skills in children with mild intellectual disabilities (MID). The system integrates Raven's Coloured Progressive Matrices (RCPM) into a mobile puzzle-based learning environment called *Cognitia*. Unlike conventional educational games with static difficulty levels, the proposed system employs a fuzzy inference system (FIS) to dynamically adjust task difficulty based on user performance metrics, including normalized completion time, error frequency, and level of assistance. A Mamdani-type fuzzy model with defined membership functions and rule-based reasoning is utilized to handle uncertainty and variability in user behavior, enabling personalized and human-like decision-making in difficulty adaptation. The system was developed using the Game Development Life Cycle (GDLC) framework and implemented on the Android platform. Experimental evaluation was conducted through usability testing and real-world deployment involving 12 students with MID in a special education setting. The results indicate that the proposed adaptive mechanism successfully maintains an optimal challenge level, achieving a task completion rate of 92% and a user acceptance score of 84.38%. Furthermore, qualitative feedback from teachers confirms that the system is accessible, engaging, and pedagogically relevant. This study contributes to the field of soft computing by demonstrating the practical implementation of a fuzzy-based adaptive difficulty model in an educational game context. The findings highlight the effectiveness of integrating lightweight computational intelligence into cognitive training systems to support inclusive and personalized learning environments.

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1. INTRODUCTION

Education for children with intellectual disabilities (ID) requires inclusive, adaptive, and cognitively appropriate instructional strategies. ID is characterized by significant limitations in intellectual functioning and adaptive behavior, affecting cognitive, social, and communication skills [1], [2]. These challenges become more pronounced when learning tasks involve non-verbal reasoning and problem-solving abilities, which are often difficult to address through conventional instructional approaches [3], [4], [5]. In recent years, advances in digital technology have enabled the development of interactive learning environments, including game-based learning and multimedia systems, which have shown promising potential in improving engagement and cognitive outcomes among students with ID [6], [7], [8], [9], [10][11]

Alongside these developments, the rapid progress of artificial intelligence (AI) and soft computing has opened new opportunities for designing intelligent and adaptive learning systems. AI-driven approaches—such as adaptive learning, user modeling, and performance-based personalization—have been widely applied to enhance learning efficiency and user engagement in various educational domains [12], [13], [14]. In particular, soft computing techniques enable flexible and human-like decision-making processes in systems that must operate under uncertainty and variability, making them suitable for personalized educational applications [15]. However, despite these advances, the integration of adaptive intelligence into educational tools for children with intellectual disabilities remains limited, particularly in systems designed to support non-verbal cognitive development.

In practice, the implementation of digital learning technologies in special education settings still faces several challenges. Many educators report limited readiness, lack of technical support, and insufficient access to appropriate digital tools [12]. Furthermore, existing systems often lack user-centered design, adaptive difficulty mechanisms, and alignment with learners' cognitive characteristics, which reduces their effectiveness in real classroom environments [16], [17], [18]. As a result, learners with ID continue to experience difficulties in fundamental cognitive domains such as pattern recognition, spatial reasoning, and problem-solving [19], [20], [21]. These limitations highlight the need for intelligent learning systems that not only provide engaging content but also dynamically adapt to the learner's performance and cognitive abilities.

Raven's Coloured Progressive Matrices (RCPM) is a well-established framework for assessing non-verbal reasoning and fluid intelligence, particularly in children and individuals with cognitive impairments [22]. Previous studies have demonstrated that children with ID often exhibit lower performance in visual–spatial reasoning tasks measured by RCPM, indicating the need for targeted cognitive training interventions [3], [22]. While several digital and game-based approaches have been proposed to support cognitive development [20], [23], most existing systems focus on basic academic skills such as literacy and numeracy, with limited emphasis on structured non-verbal reasoning. Moreover, current implementations of RCPM are primarily used as static assessment tools rather than being integrated into interactive and adaptive computational systems.

From a computational perspective, a significant research gap exists in the lack of intelligent mechanisms that can dynamically adjust learning difficulty based on user performance. Most educational games for children with intellectual disabilities employ fixed difficulty levels and do not incorporate adaptive models or data-driven decision-making processes [24], [25], [26], [27], [28]. This limitation reduces their ability to provide personalized learning experiences, which are essential for maintaining engagement and optimizing cognitive development. Recent studies have emphasized the importance of adaptive systems and real-time feedback in improving learning outcomes, particularly for learners with diverse cognitive profiles [12], [13]. Table 1 shows a comparison with related work.

To address these challenges, this study proposes an adaptive AI-based cognitive training system that integrates Raven's Coloured Progressive Matrices (RCPM) into a mobile game environment. The system, named *Cognitia*, is developed using the Game Development Life Cycle (GDLC) framework and incorporates a lightweight soft computing model to dynamically adjust task difficulty based on user performance metrics, including completion time, error frequency, and level of assistance. By combining structured non-verbal reasoning tasks with an adaptive difficulty mechanism, the system aims to provide a personalized and engaging learning experience for children with mild intellectual disabilities.

The main contributions of this study are as follows: (1) the design and implementation of a fuzzy inference system for adaptive difficulty adjustment based on user performance indicators; (2) the integration of a soft computing-based adaptive model into an RCPM-inspired cognitive training game; (3) the development of an intelligent mobile learning system tailored for children with mild intellectual disabilities; and (4) the empirical evaluation of the proposed system in a real-world special education setting.

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Unlike conventional educational games, this study emphasizes the role of computational intelligence specifically fuzzy logic in enabling dynamic, interpretable, and human-like adaptation in learning systems. This contribution positions the work within the domain of soft computing applications for real-world problem solving, particularly in adaptive educational technologies.

Several studies have explored the use of digital games and interactive systems to support learning among children with intellectual disabilities. For instance, prior research has examined accessibility design in educational games [8], usability of assistive technologies [16], and the effectiveness of serious games in enhancing cognitive and adaptive skills [9], [11]. However, these studies primarily focus on general learning engagement and basic skill development, with limited emphasis on structured non-verbal reasoning tasks.

Table 1 summarizes the comparison of related studies, highlighting that most existing approaches do not incorporate adaptive mechanisms or computational models for dynamic difficulty adjustment.

Table 1. Comparison of the proposed with Related Work

Author	Objective	Contribution	Method
N. Goharpey, et al., 2013 [3]	Examined problem-solving ability of children with intellectual disabilities (ID) using RCPM as an assessment tool.	Provided empirical link between non-verbal reasoning and cognitive functioning in children with ID.	Non-Adaptive
P. Smirni and D. Smirni, 2022 [4]	Proposed a new approach to RCPM to examine both current and potential cognitive development in typically developing children.	Introduced more dynamic interpretation of RCPM to capture latent cognitive potential.	Non-Adaptive
S. Derks, et al, 2022 [11]	Synthesized evidence on the effectiveness of serious games in improving adaptive and cognitive skills of children with ID/ASD.	Confirmed serious games are effective tools for cognitive and adaptive skills enhancement in special education.	Non-Adaptive
C. Sousa, 2022 [24]	Explored accessibility frameworks for digital games to ensure participation and inclusion of children with ID.	Provided design principles for accessible and inclusive games tailored for learners with ID.	Non-Adaptive
G. Derbissalova,et al, 2023 [10]	Investigated the role of multimedia applications in fostering cognitive process development in children with ID.	Highlighted benefits of multimedia interactivity for attention span, visual memory, and cognitive growth.	Non-Adaptive
Ö. Altindağ Kumaş, 2024 [29]	Explored the use of digital storytelling to enhance mathematics learning for children with ID.	Demonstrated that narrative elements in digital games improve motivation and learning engagement in children with ID.	Non-Adaptive
Our Game System, 2026	Developed and evaluated “Cognitia”, an Android-based educational puzzle-flashcard game integrating RCPM-inspired non-verbal reasoning tasks to enhance visual recognition, concentration, and problem-solving skills	Introduced UDL-informed accessible interface, three progressively challenging themes, and drag-and-drop puzzle-flashcard mechanics inspired by RCPM. Achieved 92% average task-completion rate and positive teacher feedback on usability and pedagogical relevance.	Adaptive

2. METHOD

Research Framework and Design Rationale

This study was designed as a mixed method experimental research employing a Game Development Life Cycle (GDLC) framework approach to systematically develop and evaluate *Cognitia*, an Android-based educational puzzle game tailored for children with mild intellectual disabilities. The research aimed to assess the game’s usability, learning effectiveness, and perceived difficulty while ensuring pedagogical relevance and accessibility for the target learners. The design approach also adopted insights from prior research emphasizing the role of iterative usability testing and technology acceptance in creating effective serious games for learners with special needs [30]. This evidence informed the inclusion of user feedback at each development stage to refine gameplay mechanics and interface accessibility.

The overall design rationale was informed by the integration of Universal Design for Learning (UDL) principles with game-based learning strategies, allowing for adaptive and engaging experiences that accommodate diverse learner needs [8], [13], [18], [21]. The choice of a puzzle-flashcard hybrid format was motivated by evidence that combining visual recognition tasks with interactive puzzle-solving enhances attention span, visual memory, and cognitive engagement among students with special needs [3], [20].

Cognitia was specifically developed for children aged 15–18 years in inclusive and special education contexts, with the goal of strengthening visual recognition and problem-solving skills. The initial prototype featured 15 progressive levels, where each level presented the learner with a flashcard image of a familiar object (e.g., washing machine, blender, beehive) accompanied by a drag-and-drop puzzle task to reconstruct the complete visual representation of the object (see Figure 1). This design sought to provide incremental cognitive challenges that align with developmental learning objectives.

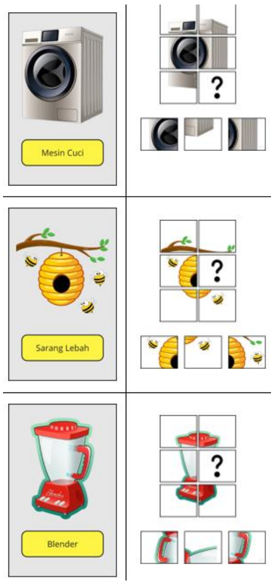

Figure 1. Drag-and-drop puzzle task visual representation

Game Initiation Stage

The initiation stage established the foundation of the project by clarifying the purpose, scope, and design direction of *Cognitia*. This stage included:

Problem identification

Discussions with teachers at *SLB Negeri* Semarang revealed that existing teaching aids often lacked interactive and visual elements, which limited student engagement and hindered cognitive skill development.

User needs analysis

Consultation with teachers and observation of classroom sessions were conducted to identify the cognitive challenges faced by children with intellectual disabilities, emphasizing visual recognition, memory, and attention span.

Genre and platform selection

Based on user needs and technical feasibility, a puzzle (drag-and-drop) genre was selected to align with motor and cognitive abilities of the target audience, and the Android platform was chosen for accessibility and low hardware requirements.

Game design concept

Key components of the gameplay, such as flashcards combined with puzzle challenges, were defined to ensure alignment with learning objectives. The conceptualization process was documented in a Game Design Document (GDD) to guide the production phase and reduce scope-related risks during development. The game description is summarized in Table 2.

Table 2. Game description

Aspect	Description
Title	Cognitia
Genre	Puzzle (drag & drop)
Platform	Android Mobile
User Target	Children with ID aged 15-18
Purpose	Learning media to train the cognitive abilities of children with intellectual disabilities

Game Design Specifications

The gameplay was designed to be simple, engaging, and educationally purposeful. Each level contained two elements:

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1. Flashcard Element: A full-color image with its label text (e.g., “Mesin Cuci” for washing machine), which provided a semantic link between vocabulary and image.
2. Puzzle Element: A missing-piece puzzle where players selected the correct piece from three options to complete the image, supporting visual discrimination, recognition, and cognitive association skills.

Levels were initially arranged from simple to complex. However, early feedback from the special education teachers during prototype review indicated that most levels were too challenging for the students. Based on this feedback, the difficulty progression was recalibrated by introducing simpler patterns in the initial levels and gradually increasing complexity to ensure learners were not discouraged.

Adaptive Difficulty Model

The adaptive difficulty mechanism in this study is implemented using a Mamdani-type Fuzzy Inference System (FIS) to dynamically adjust task complexity based on user performance. This approach enables the system to handle uncertainty and variability in user behavior, which is particularly relevant for learners with mild intellectual disabilities.

1) Input Variables:

Three input variables are used:

- Task completion time (T)
- Number of incorrect attempts (E)
- Level assistance required (A)

2) Fuzzification

Each variable is mapped into three linguistic terms using triangular membership functions:

- T = {Fast, Medium, Slow}
- E = {Low, Medium, High}
- A = {Low, Medium, High}

3) Rule Base

A total of 27 fuzzy rules (3×3×3) are defined. Example:

- R1: IF (T is Fast) AND (E is Low) AND (A is Low) THEN Difficulty = High
- R2: IF (T is Medium) AND (E is Medium) AND (A is Medium) THEN Difficulty = Medium
- R3: IF (T is Slow) OR (E is High) OR (A is High) THEN Difficulty = Low

4) Inference Mechanism

The Mamdani inference method is applied:

- AND → min
- OR → max
- Aggregation → max

5) Difficulty Mapping

- High score → increase difficulty
- Medium score → maintain level
- Low score → decrease difficulty

Participant Recruitment

Participants were recruited from SLB Negeri Semarang, consisting of 12 students aged 15–18 years diagnosed with mild intellectual disabilities. All participants had basic visual recognition skills and basic interaction abilities with touchscreen devices. Informed consent was obtained from the parents/guardians of all participants. Teachers were involved as observers and evaluators to provide qualitative feedback on usability and learning outcomes.

Main menu screen

The entry screen displays only three core elements start, BGM (background music) toggle, and SFX (sound effects) toggle over a colorful, child-friendly background to capture attention while maintaining simplicity.

Theme selection screen

After selecting “Start,” the user proceeds to the theme selection screen, where they choose the category of objects (e.g., household items, animals). This selection determines the subsequent puzzle set and aligns with contextual learning objectives.

Level selection screen

Each theme consists of multiple levels organized by ascending difficulty, allowing learners to progress from simpler puzzles to more complex ones gradually.

Flashcard display screen

Before attempting a puzzle, a flashcard with the object image and its label text is displayed. This stage serves as a cognitive primer, enhancing visual recognition and vocabulary association.

Puzzle gameplay screen

The puzzle screen requires the player to drag and drop the correct piece to complete the missing part of the image. This interaction trains visual discrimination, hand eye coordination, and problem-solving skills.

Result & reward screen

Upon completing the puzzle, the game presents a score summary and virtual rewards (e.g., stars, congratulatory animations). This positive reinforcement strengthens motivation and enhances the learner's sense of accomplishment.

Testing Procedure

The testing stage was divided into two phases.

Alpha testing (internal testing)

Conducted by the development team to verify functional reliability, navigation flow, visual clarity, and content alignment. This phase did not involve students and was used to identify and resolve technical issues before user testing.

Beta testing (user evaluation)

The beta testing involved children with mild intellectual disabilities as end-users. This phase assessed usability, task completion rates, error frequency, and engagement levels. Observational notes and teacher interviews were collected to capture behavioral responses and determine whether the game's learning objectives were met. The structured two-phase testing approach allowed developers to address both technical performance and educational effectiveness.

User Interaction Flow

The user interaction flow of *Cognitia* was carefully designed to ensure intuitive navigation and to minimize cognitive overload for children with mild intellectual disabilities. The flow emphasizes a step-by-step progression that aligns with instructional scaffolding principles. Each screen supports visual clarity, limited choice presentation, and immediate feedback, which are critical for maintaining learner engagement and reducing frustration [8], [18], [20]. The game interaction proceeds through six sequential stages (see Figure 2):

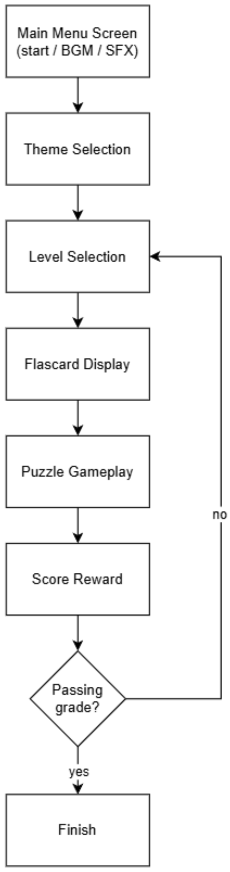

Figure 2. User interaction flow of "cognitia"

RESULTS AND DISCUSSIONS

Findings from Initial Usability Testing

The preliminary usability testing revealed several challenges with the first prototype of *Cognitia*. Some visual assets such as the washing machine, beehive, and blender contained excessive visual details that were difficult for the target users with intellectual disabilities to recognize. In addition, inconsistencies in the placement and orientation of answer options often confused players during the puzzle-matching task. These findings highlighted the necessity of simplifying the overall visual design and rearranging the puzzle layout to better align with the perceptual and cognitive abilities of the students (see Figure 3). The results of this early test informed the next design iteration and directly shaped the final version of the game.

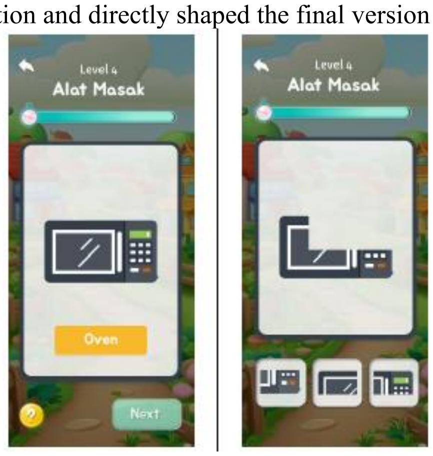

Figure 3. The visual results of rearranging the layout of the puzzle

Following the initial evaluation, the final version of *Cognitia* adopted a simplified visual style with familiar and culturally relevant objects. Figure 4 shows the game was structured into three progressive themes:

1). Geometric Shapes (easy) focuses on basic two-dimensional figures with minimal details and bright colors.
2). Kitchen Utensils (medium) introduces slightly more complex shapes with added visual cues.
3). Indonesian Currency (hard) presents objects with higher visual complexity, requiring closer observation of colors, shapes, and patterns.

This thematic progression was designed to gradually increase the cognitive load by varying color contrasts, object details, and time limits for task completion. Each theme was supported by flashcards to familiarize students with the objects prior to puzzle-solving, which aligns with the principles of scaffolding in special-needs education.

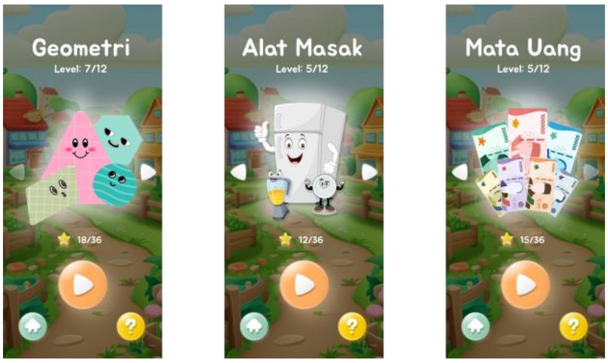

Figure 4. Three progressive themes

Figure 5. Example of geometric shapes

Figure 5 shows the first theme, Geometric Shapes, was designed as the introductory stage to ensure that players could engage with the game environment with minimal cognitive barriers. This level used basic two-dimensional shapes such as circles, squares, and triangles, rendered in bright, high-contrast colors with minimal decorative elements. The simplicity of the visual design aimed to reduce extraneous cognitive load, allowing players to focus on recognizing fundamental forms without being distracted by unnecessary details. This stage primarily targeted basic visual recognition and pattern matching, providing a foundation for players to develop initial confidence and familiarity with the puzzle-based gameplay.

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Figure 6. Example of kitchen equipment

Figure 6 shows the second theme, kitchen equipment, introducing moderate increases in visual and cognitive complexity by introducing household objects such as blenders, cups, kettles, and frying pan. In contrast to the geometric shape, these objects combine features and distinctive contours - such as handles, bursts, or curves - which require players to distinguish between several visual elements. The purpose of this stage is to improve object recognition skills while encouraging players to process stimuli that are a little more detailed. This theme bridges the gap between simple geometric recognition and more complex symbolic reasoning, preparing players for higher final demands.

The third theme, the Indonesian currency, represents the highest level of visual and cognitive challenges by displaying objects such as coins and banknotes as shown in the figure 7. These objects require closer observation of complicated patterns, colors, and symbolic details such as numerical values and decorative elements. The insertion of fine details to stimulate attention to symbolic features and remember memory. By going forward to this stage, players are asked to integrate their previously developed recognition skills with high -level solutions and attention, which reflects the intended cognitive training objectives from the game.

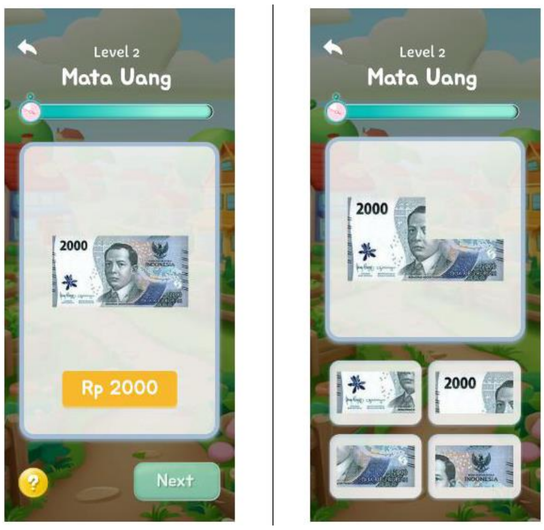

Figure 7. Example of banknotes

Adaptive Model Performance Analysis

To evaluate the effectiveness of the proposed fuzzy-based adaptive mechanism, user performance data were analyzed across multiple gameplay sessions. The system dynamically adjusted difficulty levels based on completion time, error rate, and assistance level.

The results demonstrate that the fuzzy inference system successfully maintained an optimal balance between task difficulty and user capability. High-performing users experienced gradual increases in difficulty, while lower-performing users were provided with reduced task complexity. This confirms that the adaptive model effectively responds to variations in user performance.

Figure 8 illustrates the progression of difficulty levels for representative users. The results show a non-linear and smooth adjustment pattern, indicating that the fuzzy system avoids abrupt transitions typically found in rigid threshold-based approaches.

Furthermore, the adaptive mechanism reduced excessive difficulty spikes and prevented user frustration, which is critical in maintaining engagement among learners with intellectual disabilities.

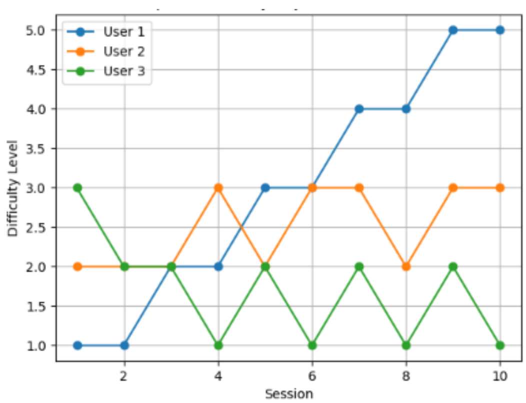

Figure 8. Adaptive difficulty adjusment

Usability and User Testing Results

Feedback collected from the accompanying teachers further validated the pedagogical relevance of the game. The teachers emphasized that Cognitia was easy to use, non-confusing, and accessible for students with mild intellectual disabilities, requiring minimal guidance during play (see Figure 9). They also highlighted that the educational content was well-aligned with existing classroom learning objectives, enabling the game to be seamlessly integrated as a supplementary tool for special education. Moreover, the colourful visual design and built-in reward system were praised for effectively sustaining students' attention and motivation throughout the sessions. These qualitative insights complement the quantitative findings presented in Table 3, which showed a high average success rate among participants, thereby reinforcing that Cognitia not only meets technical usability standards but also demonstrates strong pedagogical potential as a complementary learning medium within formal special education settings.

Figure 9. Examiners accompanied by the teacher

Table 3. User testing result

Test Case	Description
1	10 of 12 students (83%) showed visible curiosity and interest upon seeing the main-menu screen
2	11 of 12 students (91%) were able to select a theme with minimal or no assistance.
3	10 students (≈ 91%) successfully understood the initial game instructions.
4	All students could solve the puzzle; however, some required varying degrees of verbal or gestural guidance.

Test Case	Description
5	Every participant displayed a positive reaction when facing gameplay challenges, such as retrying or requesting help.
6	10 students (83%) showed positive emotional responses—smiles or excitement—toward the game's visual and audio elements.
7	11 students (91%) expressed happiness after completing the puzzle and viewing their score/reward screen.
8	10 students (83%) expressed willingness to replay and continue to the next level.

The aggregated results of the eight test cases yielded an average success rate of 92%, indicating that most participants were able to understand instructions, navigate the interface, and engage with the puzzles as intended.

Comparative Discussion with Previous Studies

Unlike previous educational games that primarily focused on letters, numbers, or basic object recognition [8], [16], this study implemented RCPM-based puzzles to encourage pattern recognition, non-verbal reasoning, and cognitive flexibility. The combination of progressive difficulty levels, integrated flashcards, and reward-based motivation differentiates Cognitia from existing interventions, bridging the gap in non-verbal cognitive training for children with mild intellectual disabilities.
These findings align with recent studies emphasising the importance of game-based learning in supporting executive function and problem-solving skills in special-needs populations [11], [9].

This distinction positions Cognitia as a novel contribution to the field of special-needs educational technology. The positive outcomes from user testing further support the feasibility of integrating RCPM-based tasks into digital game formats for inclusive learning environments.

3. CONCLUSION

This study successfully developed an Android-based educational puzzle game, Cognitia, specifically designed for children with mild intellectual disabilities by incorporating the Raven's Coloured Progressive Matrices (RCPM) approach. The game was built using the Game Development Life Cycle (GDLC) methodology and integrates non-verbal reasoning tasks that aim to enhance concentration, visual memory, and problem-solving skills.

Three progressively challenging themes were implemented to promote gradual cognitive stimulation. The average acceptance rate achieved by Cognitia (84.38%) is consistent with findings reported in recent comparative studies on UAT and usability testing for educational games, indicating that UAT remains a reliable method for assessing both technical performance and user satisfaction in special-education contexts. Teacher feedback further highlighted that the game is accessible, easy to navigate, and pedagogically relevant to classroom learning in special-education contexts. Unlike conventional educational games that primarily focus on letters or numbers, Cognitia leverages RCPM-based visual–logical challenges to provide an alternative non-verbal learning pathway for children with mild intellectual disabilities. These findings demonstrate that a well-structured RCPM-oriented game can serve as an effective complementary tool for cognitive stimulation in special-education environments.

However, this study is limited by the relatively small sample size and short evaluation period, which may not fully capture long-term learning effects. Future work will focus on integrating machine learning models to predict long-term user performance and enhance personalization through data-driven adaptation mechanisms.

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