Virtual reality to enhance mathematical skills in children with learning difficulties: design and evaluation of NumbersPlayRoom VR

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Abstract

This paper presents *NumbersPlayRoom VR*, a virtual reality serious game designed for children with learning difficulties, such as developmental dyscalculia. Based on cognitive theories of numerical processing, it leverages VR's immersive potential to enhance numeracy skills through interactive mini-games targeting visuospatial and symbolic components of mathematical reasoning. Preliminary evaluations show high usability and engagement, highlighting immersive technologies' potential for inclusive education.

Keywords

Virtual Reality, Serious Games, Dyscalculia, Learning math

1. Introduction

The acquisition of numerical skills involves complex cognitive mechanisms that engage multiple processing modalities. Children with developmental dyscalculia (DD) experience persistent difficulties in learning and manipulating numbers, and require more support and motivation[1]. DD is a learning disability that directly affects the processing and understanding of numerical information, and it can involve difficulties in estimating quantities, manipulating symbols, and performing basic arithmetic.

The cognitive basis of numerical processing is fundamental in creating effective supportive tools, especially when dealing with new technologies such as Virtual Reality (VR). Cognitive models, such as Dehaene's Triple Code [2][3], describe numerical cognition as the interaction of three systems: the analog magnitude system, the visual-Arabic code, and the verbal code. Deficiencies in the analog code, specifically the visuospatial representation of number, i.e., the mental number line, are seen as a hallmark trait of DD. Evidence from phenomena, such as the distance and SNARC effects, supports the importance of spatial-numerical associations in early number understanding[4]. In addition, children with Developmental Dyslexia often show deficits in visuospatial working memory and executive functions, which further hinder calculation skills and algebraic manipulation[5]. Many serious games have been developed to support children with dyscalculia, but almost the totality of them rely on traditional gaming experiences and platforms.

Despite existing studies highlighting VR's educational potential[6][7], the use of VR in this domain remains limited. Current research is mostly confined to laboratory settings and lacks comparison with standard methods or other game-based solutions[8]. If properly validated and implemented in teaching activities, VR can effectively provide immersive, interactive environments that support visuospatial reasoning and focused engagement. In this context, immersive technologies offer an opportunity not only to simulate engaging learning environments but also to activate multisensory processing that supports both cognitive and emotional engagement. Extended Reality (XR), especially in the form of VR, enables the embodiment of mathematical concepts through direct manipulation and

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spatial interaction, which can be especially beneficial for learners with numerical cognition difficulties. Moreover, the affective and motivational components of immersive learning environments may help reduce math-related anxiety and encourage a more positive learning experience. These features align with Mayer's Cognitive Theory of Multimedia Learning[9] as the integration of verbal, visual, and kinesthetic channels can reduce extraneous cognitive load and promote richer learning. In particular, embodied interaction and intuitive feedback may enhance engagement and retention, especially for children who struggle with abstract or symbolic representations in traditional settings.

To this end, the proposed VR game offers several key benefits for children with learning difficulties. By leveraging immersive virtual reality, it provides:

1. Increased engagement and motivation through playful interaction;
2. Dedicated training on visual-spatial and symbolic numerical components;
3. Reduced math anxiety thanks to a safe and exploratory environment;
4. Integrated multisensory feedback (visual, auditory, haptic) that reduces cognitive load and promotes the encoding of mathematical concepts through multimodal channels.

2. The NumbersPlayRoom VR Approach

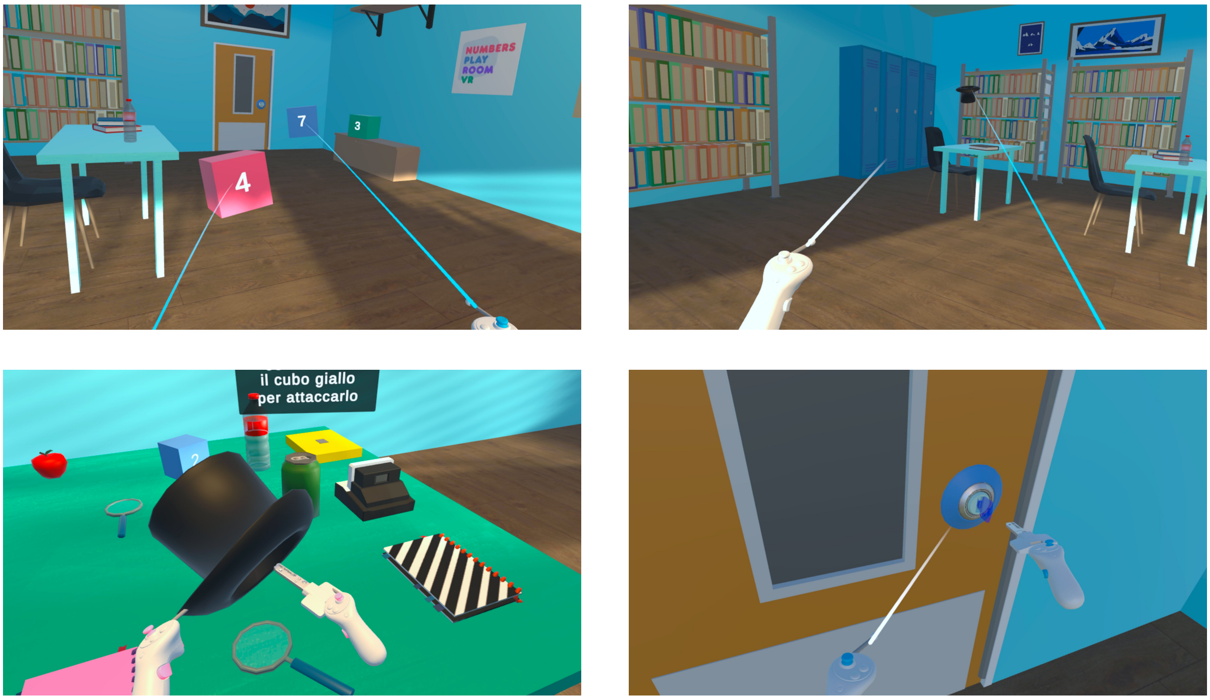

Figure 1: General screenshots: (top left) User interacting with the environment; (top right) User interacting with scattered objects; (bottom left) User performing the tutorial, learning how to grab objects; (bottom right) User inserts a previously hidden key into the lock to conclude the tutorial;

NumbersPlayRoom VR was developed as a serious game designed to address specific cognitive difficulties frequently observed in children with DD[10]. These challenges guided both the selection of numerical tasks and the implementation of VR interactions, with the goal of creating a supportive, engaging learning environment tailored to learners' needs. The game consists of a virtual space designed to be friendly and engaging, encouraging focused interaction while minimizing cognitive overload. Within this virtual environment, the user will be able to access a series of mini-games (Figure 1 and Figure 2). Two of the available mini-games are listed below:

- **Mental Calculation**: The player is presented with simple arithmetic expressions based on the chosen type and difficulty level. It must then identify the correct result among the spa-

tially distributed options (Figure 2 top left and right). This activity reinforces symbolic number comprehension and verbal retrieval, taking advantage of virtual reality-based interaction;
- **Column Counting**: The player must correctly solve an operation on the board using cards to put the number in the right position. The type of the operation and the difficulty are selected by the user (Figure 2 bottom left and right). This activity is designed to assist the user in correctly carrying out and completing operations, reinforcing their visuospatial skills in algebraic manipulation.

The game is implemented using Unity, OpenXR framework and optimized for standalone VR headsets (e.g., Meta Quest 2). The game mechanics were deliberately kept simple, with short trials, minimal text, and multimodal feedback to accommodate children with attention or language difficulties, ensuring a smooth and inclusive user experience.

An optional tutorial was also implemented to assist users new to the game or unfamiliar with interactions in VR (Figure 1 bottom right and left). Designed as a short game sequence, this section uses narrated instructions and visual cues to introduce basic actions such as teleportation, object manipulation and interaction. Each stage guides the user progressively, with clear visual cues and allowing them to learn by doing in a controlled and engaging manner. In the final stage, players must combine all previously introduced actions to complete a simple task, reinforcing learning through playful exploration before entering the main experience.

A synthesized voice provides instructions to children without overloading the screen with text, greatly improving the effectiveness of information comprehension. Users move around the room using a teleportation system, chosen to minimize the risk of motion sickness, while interacting with virtual objects through grabbing, positioning and pointing actions. Each interaction is reinforced by a combination of multimodal feedback: visual cues (such as raycast highlights), subtle tactile responses via controller vibrations, and context-specific audio signals. For example, picking up an object generates a sound and a tactile impulse, as well as pressing a button in the UI.

Similarly, correct responses are accompanied by positive sound effects and subtle vibrations, while incorrect actions trigger discreet auditory and tactile feedback that signals the error without creating frustration or stress (allowing the user to try again). Short musical stingers are also used to signal success at the end of each mini-game session, increasing the user's sense of satisfaction. These audio-tactile feedback mechanisms have been carefully designed to be informative, discrete, and positive.

The environment has been created to engage multiple sensory channels while maintaining a relaxing and reassuring atmosphere. The color combinations have been selected to provide high contrast between interactive elements and background areas, improving object recognition and visual orientation while also making the environment playful (Figure 1). The lighting has been balanced to avoid excessive contrasts or flickering that could distract or overwhelm users with sensory sensitivity, and is adjusted to keep the eye focused on the main area of interaction, while ensuring a pleasant graphic effect that significantly enhances the perception of the virtual world.

The application underwent multiple iterations based on informal feedback and design testing before a formal validation with target users. These refinements aimed to reduce potential cognitive load, clarify interaction mechanics, and ensure that all game elements were accessible and comprehensible to young users. This iterative, user-centered process allowed us to better align the mechanics and pacing of the mini-games with both the cognitive profiles and attentional rhythms of the target population.

3. Preliminary Evaluation

The development of *NumbersPlayRoom VR* was accompanied by three evaluation phases aimed at assessing usability, engagement, and educational potential. An initial informal phase involved educators, researchers, and relatives. These preliminary tests helped to verify comfort, interaction flow, and overall understanding of the in-game mechanics. Feedback led to initial refinements, such as simplifying interfaces, improving interaction feedback, and adding on-screen instructions and optional tutorials.

The second phase involved 33 young adult participants who completed both a SUS (System Usability Scale) questionnaire and a short evaluation survey. The results showed high usability and clarity

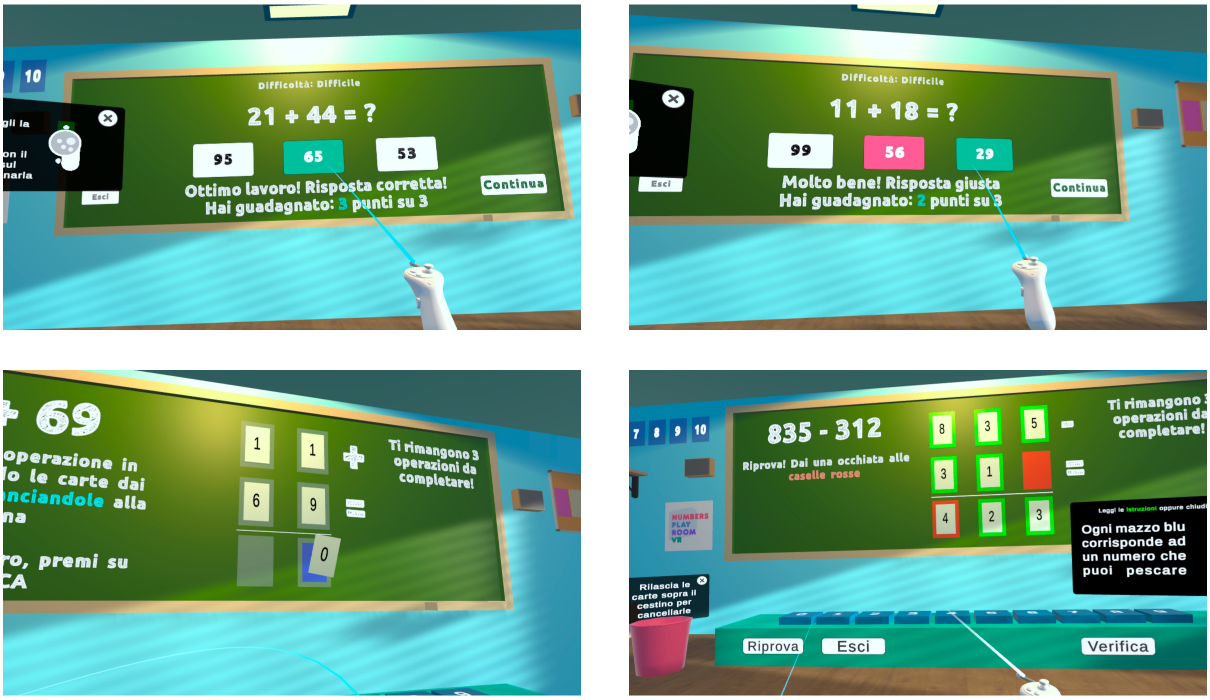

Figure 2: Mini-games screenshots: (top-left) User giving the correct answer at the first trial; (top-right) User giving the correct answer after one error; (bottom-left) User placing a numbered card on the blackboard; (bottom-right) User checking the solution, that was incorrect

(with an average SUS score of 84.17), with users reporting a good sense of engagement and immersion. Participants also perceived the mini-games as meaningful and well aligned with educational goals, suggesting potential for effectiveness. In this phase, the aim was not to evaluate the educational effectiveness of the game, but rather to test its usability, comfort and technical stability before using it with children. Involving users with greater technological familiarity enabled us to quickly collect bug reports, measure the learning curve for the controls and calibrate audio-haptic feedback, reducing the risk of frustration during subsequent school trials.

The third and most significant phase was conducted in a primary school with 34 children aged 8 to 12, including some with learning difficulties. The children played selected mini-games under adult supervision, and their experience was recorded via an emoji-based survey, co-designed with a psychologist, administered on tablets. The results were very encouraging: most reported positive emotions, low frustration, total engagement, willingness to use the application again, and full task comprehension. In particular, children diagnosed with dyscalculia or ADHD showed greater concentration and high success rates, often completing tasks accurately and independently.

Teachers provided additional observations, highlighting that some children who typically struggle to complete similar exercises in the classroom—particularly those with ADHD—performed significantly better in the VR setting. In several cases, they noted that students completed tasks such as the column counting game with focus and accuracy, whereas they would normally require assistance or abandon the activity. The immersive nature of the environment, combined with its game-based structure, may have played a key role in sustaining attention and reducing performance anxiety, allowing these learners to remain engaged and self-directed for longer periods than usual.

During the sessions, a generally positive attitude and increased confidence were also observed in many children, especially those with learning disabilities. Many participants spontaneously asked to repeat activities, and some expressed pride in having successfully completed tasks without help. The playful tone of the environment seemed to support this, helping to reduce the stress typically associated with math tasks.

These findings might also reflect, in addition to motivational aspects of game-based learning, the benefit of multisensory feedback from an attention and emotional regulation standpoint. The instantaneous auditory-haptic feedback, intuitive spatial tasks and embodied interactions may have helped to establish the user's focus and promote psychological safety and gratification in the learning environment.

At the same time, some usability issues were encountered suggesting directions for future refinements in VR interactions. Although teleportation, the most commonly used system, was adopted as a movement strategy to minimize motion sickness, some children, particularly those with ADHD, found it unintuitive or frustrating. In response, they switched to continuous locomotion, more in line with traditional video game routines. Although this provided a more familiar control experience, it also increased the risk of dizziness. This feedback highlights the necessity of hybrid locomotion models that merge the intuitiveness of free movement with the comfort of structured transitions, hence taking a step beyond the standard systems offered by XR development libraries. For example, the implementation of a fluid directional teleportation with short fade-to-black transitions can offer a balanced solution that suits different user profiles without compromising safety.

Further insights into physical interaction emerged from observing how participants behaved after completing their tasks. In some cases, it was found that some participants preferred to throw objects around the room after completing a task, perceiving it as a form of reward. This behavior suggests an opportunity to expand the use of active, physical dynamics in future iterations. Enhancing gamification through reward-based movement mechanics could further increase motivation and engagement, especially for children with high energy levels or attention problems. In addition to the structured feedback, teachers and support staff expressed interest in the potential use of the app in inclusive learning contexts, and asked about the possibility of replicating the experience in a concrete and continuous way as well. Although further controlled studies are needed, these results suggest that serious games in VR can offer valuable support for inclusive learning, particularly for students with attention or numerical processing difficulties. The encouraging responses gathered in these early stages indicate the feasibility of adopting immersive technologies as complementary tools in real-world educational settings.

4. Conclusion

This research introduces an under-investigated and targeted approach to inclusive numeracy education, combining cognitive theory with the immersive potential of virtual reality. Designed to address specific difficulties encountered by children with dyscalculia and attention disorders, the tool demonstrates how spatial interaction and embodied learning in these immersive environments can improve the understanding of numerical concepts beyond traditional methods.

Initial observations from young adult and classroom testing highlight its potential as an engaging and effective resource that can complement existing educational practices. Rather than replacing conventional teaching, this virtual reality-based tool offers a new way to reach students who benefit from alternative formats and reduced cognitive interference. While digital interventions for dyscalculia already exist, few are designed from the ground up to leverage the unique affordances of VR. This work does not aim to replicate existing activities in a new medium, but to explore how immersion, embodied interaction, and controlled spatial environments can actively support cognitive functions that are often compromised in these learners.

We actively support the ongoing development of immersive educational technologies and the research that underpins them, with a particular focus on inclusion. Although our pilot project confirms the effectiveness of *NumbersPlayRoom VR* and its ability to engage students who typically struggle with traditional mathematics, two limitations must be acknowledged. First, the study did not include a control condition based on traditional activities or 2D games, so it is not yet possible to isolate the specific contribution of virtual reality to learning progress. Secondly, the outcome measures (in terms of cognitive improvement) were mainly observational and qualitative, based on teacher assistance; no standardized pre/post assessment of numerical competence was carried out. We are therefore considering a follow-up study comparing the current VR experience with tablet exercises and worksheets with in-app analysis, in order to obtain a clearer picture of cognitive improvement and retention. Such evidence will guide the refinement of game mechanics and provide further insights into how immersive technologies can best support inclusive mathematics education.

Declaration on Generative AI

During the preparation of this work, the author(s) used GPT-4o in order to: Formatting assistance. After using these tool(s)/service(s), the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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References

[1] I. C. M. Daniela Lucangeli, Psicologia della cognizione numerica, FrancoAngeli, 2010. URL: https://francoangeli.it/Libro/Psicologia-della-cognizione-numerica?Id=18406.

[2] S. Dehaene, Varieties of numerical abilities, Cognition 44 (1992) 1–42.

[3] S. Dehaene, L. Cohen, Towards an anatomical and functional model of number processing, Mathematical Cognition 1 (1995) 83–120.

[4] J. Bachot, W. Gevers, W. Fias, H. Roeyers, Number sense in children with visuospatial disabilities: Orientation of the mental number line, Psychology Science 47 (2005) 172–183.

[5] D. B. Berch, E. J. Foley, R. J. Hill, P. M. Ryan, Extracting parity and magnitude from arabic numerals: Developmental changes in number processing and mental representation, Journal of Experimental Child Psychology 74 (1999) 286–308.

[6] M. Belter, H. Lukosch, Towards a virtual reality math game for learning in schools - a user study, in: 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 2022, pp. 808–809. doi:10.1109/VRW55335.2022.00255.

[7] P. Acevedo, A. J. Magana, B. Benes, C. Mousas, A systematic review of immersive virtual reality in stem education: Advantages and disadvantages on learning and user experience, IEEE Access 12 (2024) 189359–189386. doi:10.1109/ACCESS.2024.3489233.

[8] T. A. Mikropoulos, A. Natsis, Educational virtual environments: A ten-year review of empirical research (1999–2009), Computers & Education 56 (2011) 769–780. URL: https://www.sciencedirect.com/science/article/pii/S0360131510003052. doi:https://doi.org/10.1016/j.compedu.2010.10.020.

[9] R. E. Mayer, The Cambridge Handbook of Multimedia Learning, Cambridge University Press, 2005.

[10] M. Noro, Numbers playroom: a vr serious game to enhance children's engagement and numeracy skills, 2025. Available on https://thesis.unipd.it/handle/20.500.12608/84821.