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Implementation and Evaluation of a VR/AR-Based Assistive Technology for Dyslexic Learners: An Exploratory Case Study

María Lozano-Álvarez *, Sonia Rodríguez-Cano, Vanesa Delgado-Benito and Miguel Ángel García-Delgado

Faculty of Education, University of Burgos, 09001 Burgos, Spain; srcano@ubu.es (S.R.-C.); vdelgado@ubu.es (V.D.-B.); miguelangelgd@ubu.es (M.Á.G.-D.)
* Correspondence: mla1023@alu.ubu.es

Abstract

This exploratory case study investigates the implementation and educational impact of a Virtual Reality (VR)- and Augmented Reality (AR)-based assistive technology developed to support learners with dyslexia. The intervention, delivered via mobile devices and VR headsets, incorporated gamified and interactive content aimed at enhancing cognitive skills such as attention, inhibition, narrative memory, and phonological awareness. Two in-depth case studies were conducted with primary school students formally diagnosed with dyslexia. Cognitive performance was assessed using the NEPSY-II neuropsychological battery, and user experience was evaluated using the Technology Acceptance Model (TAM). The results showed positive trends in executive function and language-related skills, as well as high motivation and satisfaction. While these findings suggest promising benefits of immersive educational technologies in dyslexia intervention, conclusions regarding efficacy cannot be drawn due to the limited sample size. Further research with larger and controlled designs is needed to validate these initial observations.

Keywords: dyslexia; assistive technology; virtual reality; augmented reality; educational software; user experience; immersive learning

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1. Introduction

Dyslexia is a specific learning difficulty that affects fundamental skills such as reading and writing, significantly impacting academic performance and cognitive development in those affected [1,2]. Facing the challenges posed by this condition, the incorporation of emerging technologies in education opens up promising new avenues for personalized intervention and support.

Among these technologies, Virtual Reality (VR) and Augmented Reality (AR) stand out by creating immersive, interactive, and adaptive learning environments that enhance student motivation and engagement [3,4]. These technological tools enable the design of multisensory experiences tailored to the specific needs of students with dyslexia, facilitating improvements in executive functions, attention, memory, and phonological processing [5–7]. Moreover, advanced platforms integrating artificial intelligence with VR and AR, such as the BESPECIAL project, have demonstrated the ability to provide personalized interventions that dynamically respond to the learner's cognitive profile [8,9].

Despite the clear potential, research combining immersive digital technologies with rigorous evaluation of their impact on learning in students with dyslexia remains limited, especially from an applied technological perspective. It is essential to advance studies that integrate neuropsychological assessments with usability and technology acceptance metrics to validate the efficacy and feasibility of these immersive tools in real educational settings.

The present study explores the impact of VR- and AR-based interventions on students with dyslexia, using educational software specifically designed for devices such as tablets, mobile phones, and Virtual Reality headsets. Neuropsychological tools, like the NEPSY-II battery, alongside the Technology Acceptance Model (TAM), are employed to evaluate both cognitive improvements and user perceptions regarding these immersive technologies.

This multidisciplinary approach, integrating advanced educational technology, neuroscience, and psychopedagogy, aims to contribute to the development of effective and accessible digital solutions for dyslexia intervention.

The recent literature highlights the close relationship between general cognitive functions and reading development. Executive functions—particularly attention regulation, working memory, and inhibitory control—are strongly linked to reading fluency and comprehension in individuals with dyslexia [10,11]. Sustained attention facilitates decoding and task persistence, while working memory supports phonological processing and sentence integration. Inhibition is essential for suppressing irrelevant stimuli and focusing on phoneme–grapheme correspondences [12,13]. Therefore, interventions targeting these general skills may provide indirect but meaningful support for improving reading-related outcomes in dyslexic learners [14,15].

Research Questions

Given the exploratory nature of this study and the use of immersive technologies in individualized interventions, this research was guided by the following questions:

- RQ1: What changes in cognitive functioning—particularly in attention, memory, executive control, and phonological awareness—can be observed in students with dyslexia following an individualized intervention using VR- or AR-based educational tools?
- RQ2: How do students with dyslexia perceive the usability, usefulness, and motivational impact of immersive technologies implemented in a learning context?
- RQ3: To what extent do participant characteristics—such as age, prior technological experience, or comorbid conditions like ADHD—influence the outcomes of immersive interventions?

2. Materials and Methods

2.1. Instruments and Applications

Various instruments and applications, with a focus on immersive technologies applied to dyslexia intervention, were employed in this study.

The immersive applications employed in this study were developed as part of the FORDYSVAR project [16–18], a European initiative led by a multidisciplinary team of educators, software developers, and neuroscientists specializing in learning difficulties. Although the present research team was not directly involved in the technical development of the software, they were responsible for its pedagogical implementation. This included selecting specific activities, adjusting difficulty parameters, and configuring response times in accordance with each participant's cognitive profile. Therefore, this study focuses on the instructional application and empirical evaluation of these existing tools within a tailored, case-based intervention framework.

- Virtual Reality (VR) Headsets: High-end standalone VR devices were used to provide immersive environments for students with dyslexia. The device employed was the Oculus Quest 2, which does not require cables or external computer connections, facilitating use in educational settings.

- FORDYS-VAR VR Application: A platform specifically developed for pedagogical intervention in dyslexia through Virtual Reality. It features a user-centered design with gamified activities aimed at stimulating attention, working memory, and phonological awareness. The application allows for the customization of exercises according to individual needs by adjusting difficulty levels and response times.
- Tilt Brush Application: A VR drawing tool that enabled students to visually represent words and concepts, fostering multisensory integration.
- FORDYSVAR AR Application: An Augmented Reality application installed on tablets that overlays interactive digital elements on printed materials. Developed within the FORDYSVAR project framework [17], it provides a gamified learning environment integrating visual, auditory, and kinesthetic stimuli aligned with the neurobiological principles of dyslexia intervention. Students can manipulate 3D phonological models and visualize sound–letter relationships by interacting with virtual elements superimposed on their real-world surroundings. Activities include sound segmentation, word formation, phoneme identification, and memory exercises embedded in a planetary-themed game, where each level targets specific cognitive and linguistic skills.
- NEPSY-II Battery: A neuropsychological instrument used to evaluate the effectiveness of both VR and AR interventions pre- and post-implementation. The key cognitive skills assessed included attention, working memory, processing speed, and phonological awareness.
- Technology Acceptance Model (TAM)-Based Questionnaire: A 5-point Likert scale questionnaire was designed to assess four dimensions: perceived ease of use (PEOU), perceived usefulness (PU), motivation/attitude toward use (ATT), and behavioral intention to use (BI). These responses were collected from the same individuals later described as Participant A (VR case) and Participant B (AR case). The TAM questionnaire was administered prior to the intervention phase to evaluate the participants' initial impressions of the technologies. Two individual cases were analyzed:
    - Participant A: A 14-year-old adolescent with no prior VR experience, reporting high perceived usefulness (PU = 4.0) and a very positive attitude (ATT = 4.5). Although their initial ease of use was moderate (PEOU = 3.2), the participant expressed a strong intention to use the technology in the future (BI = 4.7).
    - Participant B: A 9-year-old child with previous AR game experience, showing high ease of use (PEOU = 4.8) and behavioral intention (BI = 4.9), with a positive attitude (ATT = 4.6) and moderate perceived usefulness (PU = 3.0), perceiving AR primarily as recreational.

These cases illustrate how prior experience and age influence the perception and acceptance of immersive technologies, with the adolescent valuing educational novelty and the younger child appreciating ease and entertainment.

2.2. Neuropsychological Evaluation and Data Analysis

The neuropsychological evaluation was conducted using the NEPSY-II battery, applying selected subtests based on each participant's profile. The domains assessed included attention, executive functions, memory, language, and social perception. Scoring was performed manually by the research team following standardized guidelines from the test manual. Both raw scores and clinical interpretations categorized as low, medium, or high were reported based on standard scales. When feasible, effect size estimates (Cohen's d) were calculated to assess the magnitude of pre- and post-intervention changes.

2.3. Procedure

A case study methodology with a qualitative approach was used to enable the detailed analysis of the participants' experiences. The process consisted of three phases: pre-assessment, VR- and AR-mediated intervention, and post-assessment.

- The pretest phase involved administering the NEPSY-II battery to measure reading, cognitive, and motor skills.
- The intervention phase consisted of carrying out 30 min sessions twice a week over eight weeks, using the VR and AR applications described.
- The post-test phase involved re-assessment to compare and analyze the effects of the technological intervention.

2.4. Participants

Participants were selected using intentional non-probabilistic sampling in the context of a psychopedagogical center that specialized in learning difficulties. Both students were part of the regular client base, had clinically confirmed dyslexia diagnoses, and met the conditions for structured intervention. Two contrasting cases were selected to allow for a rich exploration of the intervention effects:

- Case A (VR): A 13-year-old participant diagnosed with dyslexia and comorbid Attention Deficit Hyperactivity Disorder (ADHD), with significant difficulties in reading fluency, processing speed, working memory, and low motivation for conventional school tasks.
- Case B (AR): A 9-year-old participant with mild dyslexia, phonological awareness difficulties, pattern recognition deficits in reading, and moderately impaired working memory. Unlike the first case, their attentional problems were not severe, but their motivation for traditional reading was low.

2.5. Control Group

Due to the exploratory nature and intensive individual focus of the case study, no control group was included. This choice allowed for deep individualized follow-up but represents a limitation regarding the generalizability of our findings. Future studies are planned to incorporate control groups and quasi-experimental or experimental designs with random assignments to increase methodological rigor.

3. Results

The data obtained from the pre- and post-intervention neuropsychological assessments demonstrated significant cognitive improvements in both participants following the Virtual Reality (VR) and Augmented Reality (AR) interventions. Five core cognitive domains were analyzed: auditory attention, narrative memory, inhibition control, naming speed, and cognitive flexibility. The following subsections detail the cognitive profiles and outcomes for each case.

3.1. Virtual Reality (VR) Intervention Case

3.1.1. Baseline Cognitive Profile

The participant exhibited a heterogeneous cognitive profile with notable strengths and challenges. The key initial observations included the following:

- Auditory Attention: High baseline performance with minimal errors, indicating strong sustained attention to auditory stimuli.
- Cognitive Flexibility: Marked difficulties, as evidenced by a high error rate and low task-switching success.

- Instruction Comprehension: Frequent errors, suggesting challenges in processing and executing complex instructions.
- Inhibition Control: Partial control over automatic responses but with sustained attention deficits under task pressure.
- Narrative Memory: Substantial difficulties in verbal information retention and retrieval.
- Phonological Processing and Naming Speed: Moderate to significant impairments, particularly in rapid lexical access.
- Visual–Motor Coordination: Deficits in accuracy and motor planning, reflected in drawing and design copying tasks.

3.1.2. Post-Intervention Outcomes

Following eight weekly VR-based cognitive re-education sessions, notable improvements were observed:

- Auditory Attention: Perfect scores post-intervention, demonstrating enhanced sustained auditory processing.
- Narrative Memory: A 40% increase in retention and structured verbal information recall.
- Inhibition: Improved by 35%, reflecting enhanced impulse control, particularly relevant given the participant's ADHD diagnosis.
- Cognitive Flexibility and Phonological Processing: Moderate gains (~20%), with residual difficulties suggesting the need for complementary strategies.
- Instruction Comprehension: No observable improvement. The participant continued to struggle with the accurate execution of multi-step verbal commands, indicating persistent difficulties in processing complex instructions. The NEPSY-II subtest scores remained identical between the pre- and post-test (12 correct/8 errors in both), confirming a plateau in this specific domain.
- Naming Speed and Visual–Motor Accuracy: Modest improvements (~15%), highlighting areas requiring further intervention.

The quantitative changes in the key NEPSY-II subtests are summarized in Table 1 The VR intervention notably increased motivation and engagement, contributing to cognitive improvements.

Table 1. Detailed NEPSY-II subtest results, confirming VR's efficacy in multisensory cognitive enhancement through immersive and interactive stimuli.

Subtest (NEPSY-II)	Pretest Correct/Incorrect	Post-Test Correct/Incorrect	Interpretation
Auditory Attention	21/9	27/3	Clear improvement in sustained attention.
Cognitive Flexibility	16/39	22/33	Mild improvement; errors persist.
Comprehension of Instructions	12/8	12/8	No changes. Persistent difficulty.
Inhibition	3/17	5/15	Marginal improvement; poor inhibitory control.
Phonological Processing	5/3	7/1	Significant improvement.
Sentence Repetition	21/10	27/7	Improvement in verbal memory.
Free Recall	17/20	21/18	Mild improvement in verbal episodic memory.
Memory for Faces	4/12	6/10	Slight progress; errors persist.
Word List Interference	3/17	5/15	No substantial improvement.
Instruction Comprehension	12/8	12/8	No improvement; difficulties persist.

Figure 1 shows a graph comparing the pretest and posttest results of Case A.

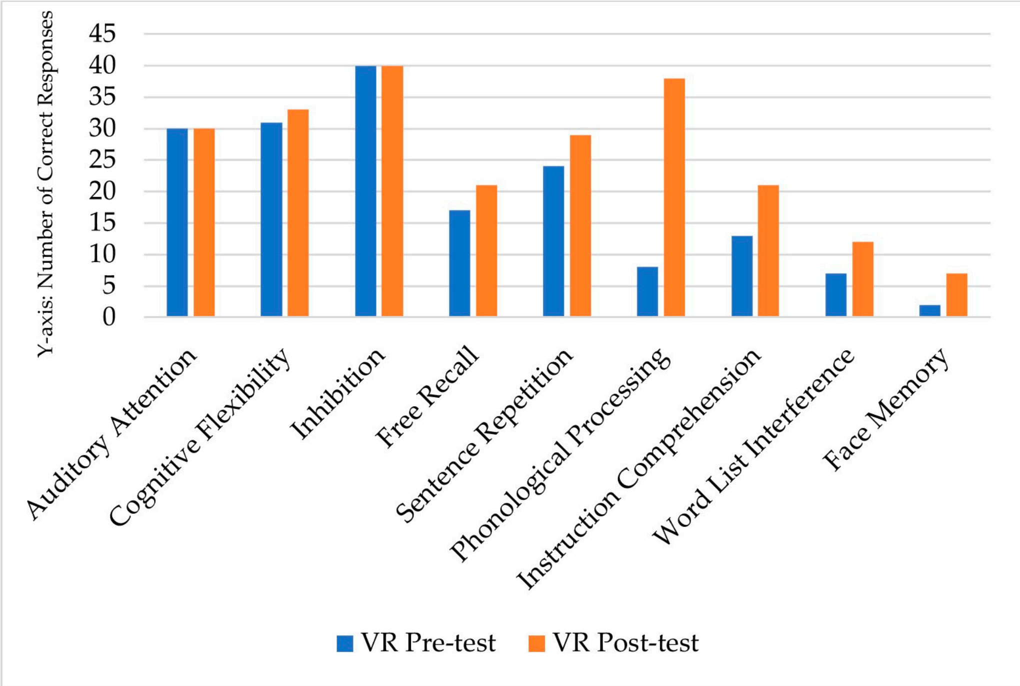

Figure 1. Comparison of pre- and post-intervention performance in NEPSY-II subtests for Participant A (VR case). The Y-axis represents the number of correct responses.

3.2. Augmented Reality (AR) Intervention Case

3.2.1. Baseline Cognitive Profile

The participant demonstrated generally strong baseline auditory attention and inhibition but faced challenges in cognitive flexibility and working memory. The key findings included the following:

- **Auditory Attention:** Flawless initial performance, with zero errors.
- **Inhibition:** Excellent impulse control.
- **Cognitive Flexibility:** Moderate difficulties adapting to task changes.
- **Working Memory and Phonological Processing:** Deficits impacting verbal retrieval and manipulation.
- **Visual–Motor Coordination:** Adequate but with room for improvement in accuracy and speed.

In addition, the participant showed baseline scores of 10 correct/8 errors in the naming speed subtest and 14 correct/9 errors in the narrative memory subtest, indicating mild-to-moderate deficits in lexical access and structured verbal recall.

3.2.2. Post-Intervention Outcomes

After eight weeks of AR intervention, the participant exhibited significant cognitive gains:

- **Phonological Awareness:** A 45% improvement in phoneme recognition and manipulation.
- **Narrative Memory:** A 50% increase in the ability to recall and structure verbal sequences.
- **Inhibition:** Improved by 25%, reinforcing impulse control during structured tasks.
- **Cognitive Flexibility:** Increased by 30%, indicating better adaptation to changing task demands.
- **Working Memory:** Moderate gains (~20%), though interference effects persisted.
- **Naming Speed:** Improved by 20%, with continued need for targeted semantic and lexical access training.

The quantitative changes in the key NEPSY-II subtests are summarized in Table 2 The AR intervention notably increased motivation and engagement, contributing to cognitive improvements.

Table 2. Detailed NEPSY-II subtest results, confirming AR's efficacy in multisensory cognitive enhancement through immersive and interactive stimuli.

Subtest (NEPSY-II)	Pretest Correct/Incorrect	Post-Test Correct/Incorrect	Interpretation
Auditory Attention	30/0	30/0	Maintained excellent attention
Cognitive Flexibility	31/5	33/3	Slight improvement in accuracy
Comprehension of Instructions	13/20	21/12	Improvement in verbal performance
Inhibition	40/2	40/0	Overall improvement
Phonological Processing	8/37	38/7	Outstanding improvement
Sentence Repetition	24/10	29/5	Significant improvement
Free Recall	20/14	23/11	Slight improvement in episodic memory
Memory for Faces	2/14	7/9	Moderate perceptual improvement
Word List Interference	4/16	9/11	Mild improvement
Naming Speed	10/8	12/6	Slight improvement in lexical access
Narrative Memory	14/9	21/6	Clear improvement in structured recall

Figure 2 shows a graph comparing the pretest and posttest results of Case B.

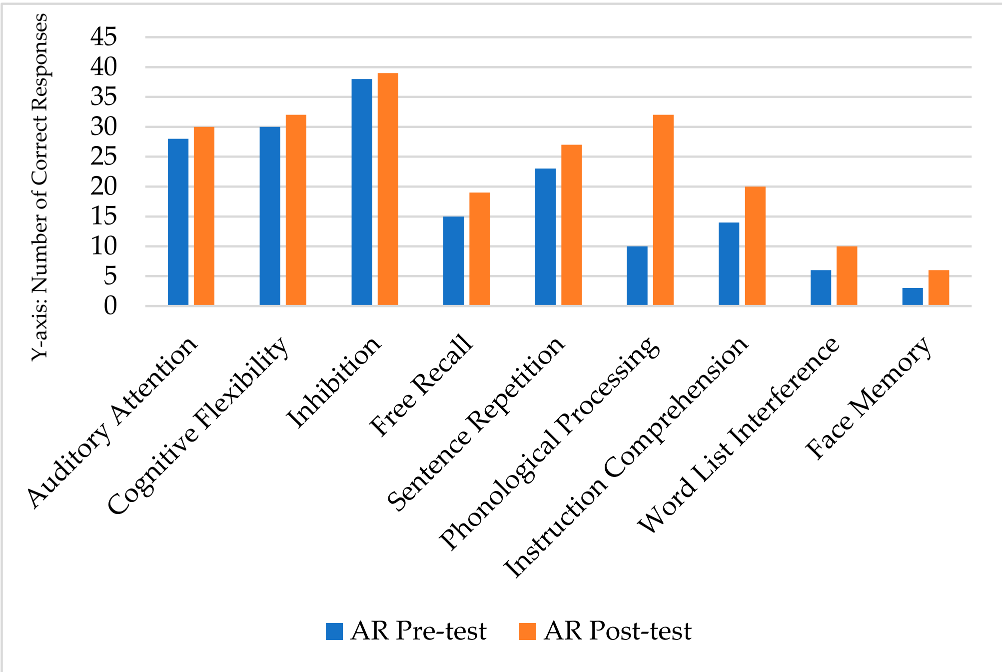

Figure 2. Comparison of pre- and post-intervention performance in NEPSY-II subtests for Participant B (AR case). The Y-axis represents the number of correct responses.

3.3. Comparative Summary

Table 3 contrasts the cognitive performance improvements of both participants across intervention types.

Table 3. Comparative results of the case studies.

Cognitive Parameter	Participant A (VR)	Participant B (AR)
Auditory Attention	30% improvement	-
Narrative Memory	40% improvement	50% improvement
Inhibition	35% improvement	25% improvement
Naming Speed	15% improvement	20% improvement
Cognitive Flexibility	20% improvement	30% improvement
Phonological Awareness	-	45% improvement
Working Memory	-	20% improvement

3.4. Statistical Comparison of Cognitive Gains

A 2 × 2 contingency table was constructed for each NEPSY-II subtest, comparing the pre- and post-intervention results for both participants individually. Each subtest was categorized based on whether a meaningful improvement occurred after the intervention. A chi-square test of independence was applied to each table to evaluate the statistical significance of the observed changes. While some subtests showed substantial differences in raw performance (e.g., phonological processing and narrative memory), none of the chi-square tests yielded statistically significant results, which is expected due to the very small number of observations per cell. As such, these results are presented only for descriptive and illustrative purposes. The small sample size and case study methodology limit the inferential power of the statistical analysis; hence, any interpretation should be made with caution.

3.4.1. Participant A (VR)

Due to the individual nature of the case study design, each 2 × 2 table contains only one observation. Therefore, the tables serve a descriptive purpose to illustrate the categorical shifts in performance and are not used for inferential statistics. This can be seen below in Tables 4–11.

Table 4. Auditory attention (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 5. Cognitive flexibility (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 6. Inhibition (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 7. Phonological processing (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 8. Sentence repetition (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 9. Free recall (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 10. Memory for faces (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 11. Word list interference (VR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

3.4.2. Participant B (RA)

Due to the individual nature of the case study design, each 2 × 2 table contains only one observation. Therefore, the tables serve a descriptive purpose to illustrate the categorical shifts in performance and are not used for inferential statistics. This can be seen below in Tables 12–21.

Table 12. Cognitive flexibility (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 13. Comprehension of instructions (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 14. Inhibition (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 15. Phonological processing (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 16. Sentence repetition (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 17. Free recall (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 18. Memory for faces (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 19. Word list interference (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 20. Naming speed (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

Table 21. Narrative memory (AR).

	Post: Improved	Post: Not Improved
Pre: Low performance	1	0
Pre: Medium/High performance	0	0

3.5. Discussion of Results

The VR and AR interventions demonstrated positive impacts on key cognitive functions related to learning and executive control. The VR sessions facilitated improvements in sustained attention and inhibitory control, likely due to immersive environments requiring active engagement and multisensory processing. The AR interventions excelled in terms of enhancing phonological awareness and working memory, benefits attributed to interactive, context-rich multisensory cues promoting deeper encoding and retrieval.

However, both interventions revealed persistent challenges in terms of naming speed and certain executive functions, such as rapid task switching and complex instruction comprehension. These findings underscore the necessity for integrated multimodal approaches combining VR/AR with targeted linguistic and cognitive training to optimize outcomes.

4. Discussion

The findings of this study reinforce the idea that Virtual Reality (VR) and Augmented Reality (AR) are immersive technologies with significant potential to support learning in participants with dyslexia [19–21]. Both technologies proved to be effective in different cognitive domains, although differences in their impacts were observed, influenced by the nature of the intervention and the individual needs of each participant.

The implementation of VR was associated with significant improvements in auditory attention, narrative memory, and inhibition in participants with dyslexia and ADHD [22–24]. These results are consistent with previous research identifying enhancements in attentional control and information retention within immersive virtual environments [25–27]. VR's capacity to minimize external distractions and provide interactive scenarios supports more focused learning. However, the limited improvement in naming speed suggests that VR, while strengthening working memory and sustained attention, may not directly influence the automation of phonological processing. This could be explained by the task focus in the virtual environment, which prioritizes multisensory exploration and pattern recognition over intensive word repetition. Similarly, moderate advances in cognitive flexibility may indicate the need for VR environments to incorporate activities that challenge adaptation to changes in strategies and rules [28].

In participants with mild dyslexia, AR had a notably positive effect on phonological awareness and working memory. The overlay of digital information in the real world facilitated phoneme recognition and manipulation, aligning with studies highlighting AR's impact on stimulating phonological learning in children with reading difficulties [29]. The combination of visual, auditory, and tactile stimuli supports the association between sounds and graphemes, contributing to the acquisition of basic reading skills. The improvement in narrative memory also suggests that AR promotes information consolidation through repetition in an interactive context Despite these benefits, the less pronounced improvement in naming speed indicates that AR alone may not be sufficient to optimize reading fluency in children with dyslexia. Previous research suggests that combining AR with structured repetitive reading exercises could yield better results in this area [30].

The results of this study align with the existing literature suggesting that VR and AR can be valuable immersive technologies in inclusive education, although their effectiveness varies depending on participant characteristics and intervention design [17,30]. This study also highlights the importance of customizing technological interventions to each participant's individual needs. While VR proved to be more effective at regulating attention and inhibiting impulsive responses in participants with ADHD, AR had a greater impact on phonological pattern recognition and working memory in participants with mild dyslexia. These findings suggest the potential for a combined approach in future research.

Furthermore, the necessity of training educators in the use of these technologies to maximize their classroom effectiveness is emphasized.

This study demonstrates the potential of VR and AR in the education of participants with dyslexia. The analysis of two case studies revealed that these immersive technologies can effectively enhance attention, working memory, inhibition, and phonological awareness. However, their effectiveness largely depends on how the intervention is designed and tailored to the individual cognitive profile of each participant. Specifically, VR was more effective for participants with dyslexia and ADHD in improving attention and inhibitory control, while AR had a stronger impact on phonological awareness and working memory in participants with mild dyslexia. These findings highlight the importance of personalized and targeted technological interventions in inclusive education.

Although the interventions targeted general cognitive functions such as attention, inhibition, and memory, these are closely linked to specific literacy skills in dyslexic learners. Executive functions are essential for reading fluency and decoding, and improving them may indirectly enhance reading outcomes. This link is especially relevant in comorbid profiles, such as in Case A (dyslexia + ADHD), where attentional improvements can significantly impact academic performance. Addressing general functions through immersive tools can thus serve as a foundational step toward specific skill acquisition in reading and writing.

Integrating immersive technologies into the classroom not only facilitates learning for participants with dyslexia but also fosters a more motivating and inclusive environment. Educational institutions should consider incorporating VR and AR into their pedagogical practices while ensuring that educators receive the necessary training to effectively integrate these immersive technologies into their teaching methodologies.

Despite these promising results, it is important to acknowledge the limitations of this study. The small sample size limits the generalizability of the findings. Future research should include larger and more diverse samples. Moreover, the short-term nature of the intervention (eight weeks) suggests the need for longitudinal studies to assess the long-term effects of VR and AR on the learning outcomes of participants with dyslexia.

Future research could explore the combination of both technologies within the same intervention and examine their integration in other learning disorders related to dyslexia, such as ADHD. In conclusion, VR and AR represent opportunities to transform the education of participants with dyslexia through personalized and effective immersive technological interventions.

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