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Original Article

The effect of virtual reality-based cognitive rehabilitation on memory and the enhancement of mathematical concept learning in students with learning disabilities

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Abstract
Background: Students with learning disabilities encounter significant cognitive and academic challenges, particularly in memory and mathematical concept acquisition. This study evaluated the efficacy of virtual reality (VR)-based cognitive rehabilitation on memory and mathematical concept learning in students with learning disabilities.
Methods: This randomized controlled trial employed a pre-test, post-test, and follow-up design with a control group. The statistical population included all male and female second and third-grade elementary students with learning disabilities receiving educational and rehabilitation services at the Dezful Developmental and Educational Assessment Center in 2024. A convenience sample of 30 participants (15 per group) was selected based on inclusion criteria and randomly assigned to either the experimental or control group. The research instruments included the N-Back working memory task and the Key-Math mathematical concept learning test. The experimental group underwent 10 sixty-minute VR-based cognitive rehabilitation sessions, while the control group received standard educational services. Data were analyzed using repeated measures analysis of variance (ANOVA).
Results: VR-based cognitive rehabilitation significantly improved memory (mean difference: 30.75 for number of correct responses, 23.18 for percentage of responses) and mathematical concept learning (mean difference: 22.50) in the post-test phase ($P < 0.001$), with effects sustained at follow-up.
Conclusion: VR-based interventions significantly enhance memory and mathematical learning in students with learning disabilities, offering a novel approach to cognitive rehabilitation.

Introduction

Learning disabilities pose significant challenges within educational systems, profoundly affecting students' academic performance, social interactions, and psychological well-being. These neurodevelopmental disorders, which include difficulties in reading, writing, and mathematics, hinder academic progress and often erode self-confidence, motivation, and self-esteem.[1] Among these, mathematical learning disability, commonly referred to as dyscalculia, is one of the most prevalent, affecting students' ability to comprehend numerical relationships, perform calculations, and solve mathematical problems.[2] Fathiazar et al[3] accentuate that learning disabilities do not arise from intellectual deficits or lack of motivation; rather, affected students typically possess cognitive capacities comparable to their peers, but their neurological processing of information differs. Grigorenko et al[4] further note that students with learning disabilities face significant obstacles in acquiring and applying skills in listening, speaking, reading, writing, and mathematics. In Iran, the prevalence of learning disabilities among students is estimated at 8.81%, with specific learning disabilities affecting approximately 5% to 15% of children, disproportionately impacting boys compared to girls.[5]

A critical factor underlying learning disabilities is the impairment of executive functions, particularly memory. Memory is integral to the learning process, facilitating the storage, retention, and retrieval of information.[6] Students with learning disabilities frequently exhibit memory deficits, particularly in working memory, which manifest as difficulties in retaining and recalling information, directly impeding their academic performance.[7] In the context of mathematical learning disabilities, working

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memory deficits exacerbate challenges in mastering complex mathematical concepts, leading to confusion and an inability to solve problems effectively.[8] Neuroscientific research indicates that these difficulties are associated with functional impairments in specific brain regions, such as the parietal lobule and prefrontal cortex. These neurological differences contribute to challenges in understanding numerical concepts, memorizing mathematical operations, and processing spatial and temporal relationships.[9]

Students with mathematical learning disabilities often struggle with basic arithmetic and foundational mathematical concepts, which can result in academic underachievement and diminished motivation. This specific learning disorder accounts for approximately 60% of all learning disability cases and is characterized by an inability to acquire computational skills commensurate with an individual's intellectual and educational level.[10] Additionally, these students frequently exhibit weaknesses in tactile tasks, visuospatial processing, self-regulation, and content organization, which further complicate their social interactions.[11] Perceptual difficulties, including issues with visual and auditory processing, as well as spatial orientation, are also common among this population.[12]

Recent advancements in technology have introduced virtual reality (VR) as a promising tool for cognitive rehabilitation in addressing these challenges. VR, defined as a human-computer interface that enables real-time interaction within a computer-generated environment, offers immersive, multi-sensory experiences that can enhance neural pathways associated with numerical processing and working memory.[13,14] Preliminary research suggests that VR-based interventions improve attention, working memory, and spatial processing, thereby facilitating the learning of mathematical concepts.[15] By providing a controlled and engaging environment for repeated practice, VR enables targeted interventions for cognitive deficits in students with mathematical learning disabilities.[16] Through immediate feedback and interactive simulations, VR-based approaches enhance focus, strengthen memory, and promote more effective learning of mathematical concepts.[17] Studies, such as those by Nazarboland et al,[18] have demonstrated that computer-based cognitive rehabilitation improves working memory, sustained attention, and mathematical performance in children with neurodevelopmental disorders, such as autism spectrum disorders. Similarly, Barati et al[19] found that VR-based rehabilitation significantly improved executive functions, including selective attention, sustained attention, and response inhibition, with the most notable gains observed in selective attention.

This study is significant for several reasons. First, it leverages innovative VR technology to address the limitations of traditional interventions for mathematical learning disabilities, offering a novel approach to cognitive rehabilitation. Second, it integrates the enhancement of cognitive functions, such as memory, with the development of academic skills in mathematics, potentially yielding more sustainable outcomes. From a practical perspective, the findings could inform the design of personalized educational programs and cognitive rehabilitation software tailored to the needs of students with learning disabilities. Conducting this research within the Iranian cultural and educational context, specifically in Dezful city, further contributes to the localization of knowledge in this field. Based on these considerations, this study aims to evaluate the efficacy of VR-based cognitive rehabilitation in improving memory and mathematical concept learning among students with learning disabilities.

Methods

This study utilized a randomized controlled trial (RCT) design with pre-test, post-test, and follow-up assessments, incorporating a control group. The statistical population consisted of all male and female second and third-grade elementary students diagnosed with learning disabilities, receiving educational and rehabilitation services at the Dezful Developmental and Educational Assessment Center in 2024. A convenience sample of 30 students (15 in the experimental group and 15 in the control group) was selected based on inclusion criteria, including a formal diagnosis of a learning disability by an educational psychologist, an age range of 7 to 9 years, and the absence of co-occurring major psychiatric disorders. Exclusion criteria included non-cooperation during intervention sessions or absence from more than two consecutive sessions. A sample size calculation was performed using G*Power software, determining that a minimum of 28 participants (14 per group) was required to detect a medium effect size ($f = 0.25$) with 80% power and an alpha of 0.05 for repeated measures ANOVA. To account for potential attrition, 30 participants were recruited. Participants were randomly assigned to either the experimental or control group using a random number generator to minimize allocation bias. Written informed consent was obtained from parents, ensuring the confidentiality of all data.

Instruments

N-Back Working Memory Task

The N-Back task is a standardized measure of working memory, widely used in cognitive and neuroimaging research.[20] Participants view a sequence of visual stimuli and determine whether the current stimulus matches the one presented 'n' steps earlier. In this study, the 2-back task was employed, suitable for children with learning disabilities due to its moderate difficulty. The task yields two primary scores: the number of correct responses (raw count of accurate matches) and the percentage of correct responses (proportion of correct responses relative to total trials). In this study, the N-Back task was adapted for

Iranian children, with stimuli presented in Persian, and its reliability was assessed using Cronbach's alpha, yielding values of 0.80 for the number of correct responses and 0.83 for the percentage of correct responses. Although the N-Back task has been validated in diverse populations, specific validation studies for Iranian children with learning disabilities are limited; however, its established use in similar neurodevelopmental populations supports its applicability.[20]

Key-Math mathematical concept learning test

Developed by Suntup, the Key-Math test assesses mathematical comprehension in children aged 6 years 6 months to 11 years 9 months.[21] It includes three sections—Basic Concepts, Operations, and Applications—with 13 subtests evaluating skills such as counting, arithmetic operations, and problem-solving. Raw scores from each subtest are summed and converted to Z-scores based on grade-specific norms, with higher Z-scores indicating greater mathematical proficiency. In this study, the test was administered in Persian, with cultural adaptations to ensure relevance. The Cronbach's alpha for the test was 0.84, indicating good reliability. While the Key-Math test is widely validated, its specific psychometric properties in Iranian children with learning disabilities have not been extensively studied; however, its alignment with educational curricula in Iran supports its suitability.[21]

Intervention

The VR-based cognitive rehabilitation program consisted of 10 sixty-minute sessions, delivered twice weekly to the experimental group, focusing on enhancing working memory and mathematical concept learning. The intervention utilized an Oculus Quest 2 headset running custom-designed software developed on the Unity platform, tailored for children with learning disabilities. The software included interactive 3D environments with exercises targeting numerical skills, problem-solving, and memory retention, incorporating gamified elements to maintain engagement. Sessions were conducted in a controlled setting at the Dezful Developmental and Educational Assessment Center, supervised by trained educational psychologists. The control group received standard educational services without VR intervention. Session details are summarized in Table 1.

Data analysis

Data were analyzed using SPSS version 26. Repeated measures ANOVA was employed to evaluate the intervention's effectiveness on memory and mathematical concept learning across time (pre-test, post-test, follow-up) and between groups (experimental vs. control). Assumptions for ANOVA were tested: normality was confirmed using the Kolmogorov-Smirnov test ($P > 0.05$ for all variables), sphericity was assessed using Mauchly's test ($P > 0.05$, indicating no violation), and homogeneity of variance was verified using Levene's test ($P > 0.05$). Effect sizes were calculated using partial eta squared ($\eta^2 p$) to quantify the magnitude of intervention effects. Post-hoc pairwise comparisons were conducted using the LSD test, with Bonferroni correction applied to adjust for multiple comparisons to control the Type I error rate. Descriptive statistics (means and standard deviations) were reported for all dependent variables across measurement phases.

Results

The demographic data of the participating students revealed that among the total of 30 participants, 16 were in the second grade and 14 were in the third grade of elementary school. Furthermore, the sample consisted of 21 male students and 9 female students. The age range of the participants, based on their grade levels, was consistently between 7 and 9 years old. Table 2 presents the means and standard deviations for the dependent variables—memory (number of correct responses), memory (percentage of responses), and mathematical concept learning—across the three measurement phases: pre-test, post-test, and follow-up. As observed, the experimental group generally showed an increase in mean scores from pre-test to post-test and follow-up across all dependent variables, whereas the control group's scores remained relatively stable or showed minimal change.

Before inferential analyses, assumptions for repeated measures ANOVA were tested. The Kolmogorov-Smirnov test confirmed normality for all dependent variables—memory (number of correct responses, $P = 0.200$), memory (percentage of responses, $P = 0.200$), and mathematical concept learning ($P = 0.200$). Mauchly's test indicated no violation of sphericity ($P > 0.05$), and Levene's test confirmed homogeneity of variance ($P > 0.05$). Repeated measures ANOVA results (Table 3) revealed significant main effects of time for all dependent variables ($P < 0.001$), with large effect sizes: memory (number of correct responses, $\eta^2 p = 0.70$), memory (percentage of responses, $\eta^2 p = 0.77$), and mathematical concept learning ($\eta^2 p = 0.74$). The time × group interaction was also significant ($P < 0.001$) for all variables, with effect sizes of $\eta^2 p = 0.69$, $\eta^2 p = 0.78$, and $\eta^2 p = 0.75$, respectively, indicating differential changes between groups over time. Between-group effects were significant ($P < 0.001$), with large effect sizes ($\eta^2 p = 0.96$ for memory number of correct responses, $\eta^2 p = 0.94$ for percentage of responses, $\eta^2 p = 0.93$ for mathematical concept learning), confirming the intervention's impact.

Post-hoc analyses with Bonferroni correction (Table 4) revealed significant differences between pre-test and post-test ($P < 0.001$, Cohen's $d = 2.12$ for memory number of correct responses, $d = 2.45$ for percentage of responses, $d = 2.31$ for mathematical concept learning) and between pre-test and follow-up ($P < 0.001$, $d = 2.34$, $d = 2.76$, $d = 2.49$, respectively) for all variables. Differences between post-test and follow-up were significant for

Table 1. Summary of VR-based cognitive rehabilitation program sessions

Session	Primary objective	Key activities
1	Introduction to VR environment and basic memory exercises	Introduction to the VR system, simple object identification, and pattern matching exercises in a virtual environment.
2	Enhancement of visual memory and number sequencing	Visual memory games with numbers, following numerical patterns in the VR environment.
3	Numerical working memory practice	Solving simple math problems using virtual objects, practicing retention and manipulation of numbers in the mind.
4	Reinforcement of spatial and geometric memory	Identification of geometric shapes, arrangement of objects in a 3D virtual space.
5	Learning addition and subtraction concepts in VR	Interactive exercises for addition and subtraction using virtual objects and scenarios.
6	Enhancement of auditory memory and following instructions	Games require listening and following multi-step instructions in the VR environment.
7	Learning basic multiplication and division concepts	Engaging multiplication and division exercises with visual simulations and immediate feedback.
8	Solving verbal mathematical problems	VR scenarios require understanding and solving simple verbal math problems.
9	Combined memory and math exercises	Games and activities simultaneously engage visual, auditory, and mathematical memory.
10	Review and consolidation of learned concepts	Repetition of more challenging exercises and assessment of progress within the VR environment.

Table 2. Mean and standard deviation of research variables at pre-test, post-test, and follow-up phases

Variable	Group	Pre-test	Post-test	Follow-up
		Mean (SD)	Mean (SD)	Mean (SD)
Memory (number of correct responses)	Experimental	47.75 (5.79)	78.50 (7.39)	81.69 (5.82)
	Control	45.53 (5.17)	45.47 (6.28)	45.65 (5.15)
Memory (percentage of responses)	Experimental	38.63 (3.46)	61.81 (4.56)	68.13 (5.87)
	Control	37.76 (3.21)	36.18 (4.15)	37.94 (4.86)
Mathematical concept learning	Experimental	45.63 (4.17)	68.13 (3.57)	72.25 (4.42)
	Control	45.24 (3.83)	45.12 (4.56)	44.35 (5.54)

Table 3. Results of repeated measures ANOVA for within-group and between-group effects

Source	Variable	SS	df	MS	F	*P*
Time	Memory (number of correct responses)	5805.463	2	2902.731	65.053	0.001
	Memory (percentage of responses)	3880.705	2	1940.352	93.656	0.001
	Mathematical concept learning	3228.132	2	1614.066	78.878	0.001
Time × Group	Memory (number of correct responses)	5775.281	2	2887.640	64.714	0.001
	Memory (percentage of responses)	4105.796	2	2052.898	99.088	0.001
	Mathematical concept learning	3550.072	2	1775.036	86.744	0.001
Group	Memory (number of correct responses)	13963.565	1	13963.565	783.798	0.001
	Memory (percentage of responses)	8826.645	1	8826.645	501.238	0.001
	Mathematical concept learning	7228.844	1	7228.844	416.138	0.001

Table 4. Pairwise comparisons of measurement phases for variables using the LSD post-hoc test

Variable	Compared phases	Mean difference	Std. error	*P*
Memory (number of correct responses)	Pre-test - Post-test	30.75	2.97	0.001
	Pre-test - Follow-up	33.93	2.20	0.001
	Post-test - Follow-up	3.18	2.60	0.644
Memory (percentage of responses)	Pre-test - Post-test	23.18	1.34	0.001
	Pre-test - Follow-up	29.50	1.46	0.001
	Post-test - Follow-up	6.31	2.12	0.009
Mathematical concept learning	Pre-test - Post-test	22.50	1.42	0.001
	Pre-test - Follow-up	26.62	1.45	0.001
	Post-test - Follow-up	4.12	1.31	0.007

memory (percentage of responses, $P=0.009$, $d=0.62$) and mathematical concept learning ($P=0.007$, $d=0.58$), but not for memory (number of correct responses, $P=0.644$), suggesting sustained or further improvement in some domains. These trends are visually represented in Figure 1, which illustrates the mean scores for memory (number of correct responses and percentage of responses) and mathematical concept learning across the pre-test, post-test, and follow-up phases for both the experimental and control groups.

Discussion

The current study demonstrated that VR-based cognitive rehabilitation significantly enhanced memory and mathematical concept learning in students with learning disabilities, with sustained effects at follow-up. These findings highlight VR's potential as an innovative tool for addressing cognitive and academic challenges in this population. The significant improvements in memory performance, particularly in the number and percentage of correct responses, may be attributed to VR's immersive and interactive nature, which engages multiple sensory modalities and promotes neuroplasticity in brain regions associated with working memory, such as the prefrontal cortex.[13,22,23] By providing a dynamic environment for practicing memory tasks, VR likely facilitates stronger encoding and retrieval processes, which are critical for students with learning disabilities who often exhibit working memory deficits.[7] This aligns with Nazarboland et al.[17], who reported enhanced working memory in children with autism spectrum disorders following computer-based cognitive training, suggesting that technology-mediated interventions leverage similar cognitive mechanisms across neurodevelopmental conditions.

The marked improvement in mathematical concept learning underscores VR's ability to transform abstract mathematical concepts into tangible, interactive experiences. For students with dyscalculia, who struggle with numerical relationships and arithmetic operations[2], VR's visual and spatial simulations may reduce cognitive load and enhance comprehension by providing concrete representations of abstract concepts.[24,25] For instance, manipulating virtual objects in 3D space during sessions targeting geometry and arithmetic likely supported visuospatial processing, a known deficit in this population.[12] The immediate feedback provided in VR environments further reinforces learning by allowing students to correct errors in real-time, fostering self-regulation and engagement.[17] This is consistent with Barati et al,[19] who found VR-based rehabilitation improved executive functions like attention, which are foundational to mathematical reasoning. Unlike traditional instructional methods, which often rely on rote memorization and abstract symbols, VR offers a multisensory, experiential approach that may be particularly effective for students with learning disabilities.[26]

The sustained effects at follow-up suggest that VR-based interventions may induce lasting changes in cognitive and academic abilities. This durability could stem from VR's ability to create engaging, repeatable learning experiences that promote skill consolidation and transfer to real-world contexts.[22,24] However, the study's limitations

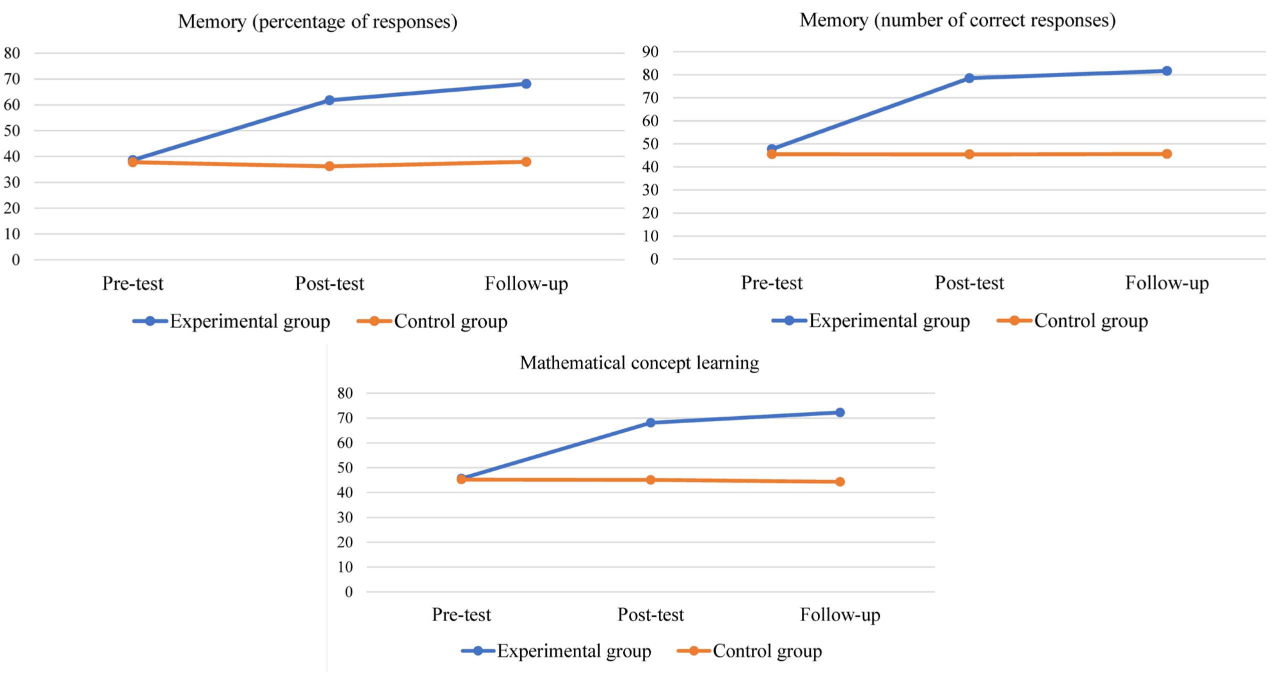

Figure 1. Mean scores of memory (number of correct responses and percentage of responses) and mathematical concept learning across pre-test, post-test, and follow-up phases for experimental and control groups

must be acknowledged. The small sample size (n = 30) and convenience sampling method limit generalizability, as the participants may not fully represent the broader population of students with learning disabilities. The absence of blinding (e.g., teachers or parents aware of group assignment) may have introduced bias, potentially influencing outcomes through differential expectations or support. The lack of long-term follow-up beyond a few months restricts conclusions about the intervention's enduring impact. Additionally, while the N-Back and Key-Math tests were reliable, their specific validation in Iranian children with learning disabilities is limited, warranting caution in interpreting their applicability. Future research should incorporate larger, more diverse samples, blinded designs, and extended follow-up periods to validate and extend these findings. Integrating recent meta-analyses, such as Benavides-Varela et al[11] and Jiang et al,[26] which highlight VR's efficacy in supporting mathematical learning and STEM education, could further strengthen the theoretical framework.

Conclusion

This study conclusively demonstrates that VR-based cognitive rehabilitation significantly enhances both memory function and mathematical concept learning in students with learning disabilities. The sustained positive effects observed at follow-up highlight the long-term efficacy and robust nature of this intervention. These findings underscore the transformative potential of VR technology as an innovative and effective tool for cognitive rehabilitation, offering a promising pathway to improve academic outcomes and address the unique educational needs of students with learning disabilities. This research provides a strong foundation for integrating immersive technologies into specialized educational programs.

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Authors' Contribution

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Writing–review & editing: Fariba Hafezi, Amal Sharifi Fard, Reza Johari Fard.

Competing Interests

The authors declare no conflict of interest.

Ethical Approval

The ethical conduct of this study was thoroughly scrutinized and approved by the Ethics Committee of Islamic Azad University, under the specific approval code IR.IAU.AHVAZ.REC.1403.368.

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