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The Effectiveness of Augmented Reality-Based Training on Working Memory Performance and Cognitive Flexibility in Children

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ABSTRACT

Objective: Information and Communication Technology (ICT) holds significant potential for enhancing children's knowledge and skills by enabling personalized learning, multisensory approaches, and increased content engagement. Augmented Reality (AR), specifically, offers novel learning pathways and improves the quality of conventional education by merging real-world environments with virtual content. This study aimed to examine the effectiveness of Augmented Reality-Based Training (ARBT) on working memory performance and cognitive flexibility in children.

Method: A quasi-experimental design with pretest-posttest and control/experimental groups was employed. The population consisted of 3,612 fifth-grade students in Aqqala County during the 2022-2023 academic year. Using cluster sampling, 36 children were selected as the research sample. Data were collected using Dennis and Vander Wal's (2010) *Working Memory Questionnaire (WMQ)* and *Cognitive Flexibility Inventory (CFI)*. Content validity was confirmed by experts in psychology and education after minor revisions, and reliability was.established via Cronbach's alpha coefficients (.71 for WMQ, .74 for CFI). Data were analyzed using SPSS-26 through descriptive (frequency, percentage) and inferential statistics (Kolmogorov-Smirnov test, ANCOVA).

Results: The results indicated that Augmented Reality-Based Training had a significant positive effect on children's working memory performance (Pillai's Trace = .85, $F = 58.74$, $p<.001$, partial $\eta^2 = .85$) and cognitive flexibility (Pillai's Trace =.80, $F = 64.15$, $p<.001$, partial $\eta^2 = .80$).

Conclusions: Augmented Reality-Based Training significantly enhances children's working memory and cognitive flexibility, thereby improving key functions like attention and problem-solving.

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Introduction

Information and Communication Technology (ICT) can profoundly enhance children's knowledge and skills through personalized learning, multi-sensory methods, and fostering richer interactions with educational content. A key innovator in this domain, Augmented Reality (AR), creates novel learning pathways by seamlessly blending digital elements into the physical world. This integration not only elevates the quality of traditional education but also redefines it as a highly interactive, multi-sensory, and engaging process (Sarafraz et al., 2025).

Augmented Reality (AR) is a technology that superimposes virtual information—such as images, data, or 3D models—onto the real-world environment in real time. This overlay enhances the user's interaction with and perception of their immediate surroundings (Emadi Sadeghi et al., 2023). Fundamentally, AR operates as an interactive medium that spatially and temporally blends digital data with the user's physical environment in real time (Hobbs & Bull, 2025; Sadeghi & Karimi, 2019).Augmented reality can activate learning content in three-dimensional perspectives, co-located, collaborative, and situational learning, the presence of the senses, the presence of the mind, and the immersion of learners, the invisible body, and the connection of formal and informal learning (Khatereh et al., 2010; Wu et al., 2013). Augmented reality is a bridge between the real and virtual worlds that is created by adding virtual information created by the computer (Carmigniani & Furht, 2011). Interaction enhances the user's individual knowledge and understanding of the real world in real time (Pantelić & Vukovac, 2017). This technology also adds combined and complementary information from the users' perspective to a page by adding animation, virtual objects, 3D images, video, audio, and similar items to a page, which can improve the excitement, participation, and enjoyment of users, as well as their learning and cognitive layer in the interactive interaction process (Jetter et al., 2018). The elements of augmented reality found in numerous studies can increase children's motivation, participation, and satisfaction during learning activities (Ibáñez et al., 2015) and make the learning area attractive, interactive, and exciting. Furthermore, these capabilities—particularly the visualization of abstract concepts and natural interaction—reduce cognitive load and enhance information encoding. This process directly facilitates the temporary storage and manipulation of information, which is the core function of working memory (Kim & Choi, 2025).

Working memory is a part of the human memory system that uses cognition to temporarily hold information in an active state in order to perform complex operations on it, and it acts as a way station for long-term memory (Rahmani Doqaruni, 2024). In other words, working memory is the ability to maintain information in the mind while performing complex tasks and includes the ability to monitor performance and evaluate cognitive processes. As a mental system, it is responsible for temporarily storing and processing information to perform complex cognitive tasks (Abbasi &

Tabatabaee, 2022) and predicts success in daily activities such as following instructions, mental calculations, and problem solving (Azizi Mahmoudabad et al., 2019). In working memory, information obtained from the environment is compared with information stored in long-term memory; desired decision is selected, organized, and prepared for execution (Meltzer & Krishnan, 2007; Rahaei et al., 2022). Baddeley (2010) considers working memory to consist of three components: the phonological loop, the visuospatial model, and the central executive (Jaeggi & Buschkuehl, 2014). The phonological loop is a specific area of storage that is responsible for the temporary storage of verbal and auditory information. This subcomponent is essential for language learning (Kokubo et al., 2012). The visuospatial sketchpad also stores visuospatial information. Although the visuospatial model itself is considered as a single subcomponent, it can be divided into two more detailed subcomponents: visual and spatial (Dadashnejhad et al., 2022). The visual subcomponent is responsible for storing visual information (e.g., information related to shapes and colors), and the spatial subcomponent is responsible for storing spatial information (for example, information related to directions) (Jaeggi & Buschkuehl, 2014). The central executive is a supervisory system used to control and regulate cognitive processes. This part draws attention to the stimulus and identifies the items that need to be stored (Dehan, 2008). In general, working memory is a mental workspace that allows temporary storage and manipulation of information in the mind. The functioning of this component is essential to facilitate and correctly perform the activities of other components of executive functions, and its proper functioning provides concentration, sustained attention, reflection in response to stimuli, and inhibition of irrelevant impulses (Ghasemian-Moghaddam et al., 2018; Shamshiri et al., 2025).

Through its core features—such as immersive three-dimensional visualization, collaborative scenarios, and situational learning—Augmented Reality (AR) creates dynamic environments that require users to continuously adapt their thinking, shift perspectives, and manage multiple streams of information. These cognitive processes are fundamental to developing enhanced cognitive and psychological flexibility (Bhambri, 2025). Cognitive flexibility is the ability to simultaneously manage multiple aspects of a cognitive task, which allows an individual to actively exert control over cognitive processes (Carbonella et al., 2016; Deak et al., 2015). To change attention within one's mental set (Dennis & Vander Wal, 2010) or after receiving negative feedback (Francazio & Flessner, 2015) to adapt to the changes made, change one's cognitive set and consequently one's behavior (Homayouni et al., 2024). A distinctive feature of human cognitive flexibility is the ability to change the course of target behavior to respond to changing demands. Cognitive flexibility is responsible for changing and regulating human emotions using learning tasks (Passolunghi & Costa, 2019). People with cognitive flexibility are aware of study strategies and focus on decision-making and problem-solving. Such strategies are used in academic contexts and allow them to feel competent in completing academic and social tasks (Bilgiç & Bilgin, 2016; Savari, 2020). Bigdali et al. (2017) in a study showed that people who are cognitively inflexible turn to rumination when upset and focus their cognitive energy on these repetitive and unproductive responses.

Supli and Yan (2024) investigated the effectiveness of augmented reality in strengthening elementary school students' spatial reasoning skills, including mental rotation, spatial orientation, and spatial visualization. Their findings demonstrated that AR training had a significant positive effect on these skills. Similarly, Lim et al. (2023) developed augmented reality-based applications to test brain memory function. They found that students performed better on an AR-based visual memory test compared to physical and computer-based modes. Furthermore, EEG data indicated that students were more engaged and attentive when using AR technology. Research also supports AR's effectiveness in addressing academic emotions. Pourghaz et al. (2019) studied the effect of AR-based education on children's math anxiety and academic enthusiasm. They concluded that this approach significantly reduces math anxiety while increasing academic enthusiasm. For students with learning differences, Khatri et al. (2010) focused on dyslexic children in the second grade. Their research confirmed that using AR technology significantly increased the children's learning, suggesting it is a valuable tool for this population. Finally, in a study entitled "Designing a Cognitive Flexibility Training Program and Investigating Its Effect on Reducing Behavioral Problems in Mentally Retarded Adolescents," Arjomandnia et al. (2020) concluded that such training can reduce behavioral problems. The authors suggest that by developing techniques to increase cognitive flexibility, therapists can open new horizons for addressing behavioral issues in this group."

Numerous studies have established the critical relationship between working memory and academic performance. Research findings by Allen et al. (2019), Bedyńska et al. (2019), Passolunghi and Costa (2019), and Fuchs et al. (2019) have concluded that working memory plays a vital and decisive role in learning, performing complex cognitive tasks, and problem-solving. Therefore, problem-solving strategies are intrinsically linked to working memory. In a study on augmented reality for facilities management tasks, Liu and Seipel (2018) concluded that positioning performance increased significantly and was enhanced by AR. They also found that with AR visual guidance, the closest predicted position of virtual objects on the surfaces of real-world structures can be determined. Furthermore, Tolabi et al. (2018) investigated the effect of working memory on students' cognitive problem-solving. They concluded that working memory capacity (differentiating individuals with high versus low effective capacity) had a significant impact on students' problem-solving performance. This finding underscores the necessity of acknowledging the pivotal role of working memory capacity in an individual's problem-solving ability.

In light of the above, it can be argued that Augmented Reality (AR) technology enhances children's active participation in knowledge construction by providing novel interactive experiences, strengthening spatial reasoning skills, and improving memory functions. Consequently, it emerges as a valuable tool for classroom integration. Working memory—a core cognitive system responsible for temporary storage and information processing—facilitates focused and sustained attention, comprehensive perception, and effective decision-making when optimally functional. Cognitive flexibility, defined as the ability to adapt to changing conditions, centers on decision-making styles and problem-coping strategies.

However, despite the well-documented individual benefits of AR and the critical roles of working memory and cognitive flexibility, there is a scarcity of research that empirically examines the direct impact of structured AR-based training programs on these two specific cognitive processes concurrently in children. This gap underscores the necessity of conducting the present study to provide robust evidence on how targeted AR interventions can be harnessed to foster essential cognitive skills in educational settings. Thus, given the significant benefits of AR and the impact of working memory performance and cognitive flexibility on children's psychological and academic processes, this research sought to probe what effects Augmented Reality-Based Training has on working memory and cognitive flexibility in children.

Materials and Methods

Research Design and Participants

The present study used a quasi-experimental method with a pre-test and post-test design, including both control and experimental groups. The study population consisted of 3612 fifth-grade children in Aqqala County during the 2022-2023 academic year. Considering the risk of type 1 error at the 5% level, the power of the test was .8, and the sample size was calculated to be 36 people. The effect size was considered according to the study by Pouraziz and Aliabadi (2019). They reported a partial eta square of 0.85 in the use of augmented reality technology on learning.

Cluster sampling was employed to select the research sample through a multi-stage random process to ensure representativeness and minimize selection bias. First, all primary schools in Aqqala County were stratified into two separate lists based on students' gender (boys' and girls' schools). One school was then randomly selected from each list using a computer-based random number generator (e.g., the RAND function in Microsoft Excel). Within each selected school, one fifth-grade class was chosen randomly via a lottery method from all available classes at that grade level. Finally, from the official student roster of each selected class, 18 students were selected using systematic random sampling (e.g., selecting every 2nd student from a randomly ordered list). This procedure yielded a final sample of 36 participants (18 male and 18 female students).

The inclusion criteria for participation in the study were: mental and physical health (based on educational records), normal intelligence ($IQ \geq 85$, based on educational records), and willingness to participate. The exclusion criteria included withdrawal due to fatigue during the research process. The selected children were then assigned to either the control or experimental group, ensuring homogeneity between the groups with respect to IQ and gender.

Instruments

Working Memory Questionnaire (WMQ)

Working Memory Questionnaire was developed by Dennis and Vander Wal (2010) including a 30-item self-report instrument utilizing a six-point Likert scale (0-4). It was designed to assess challenges associated with working memory deficits across three distinct domains: short-term storage (items 1-10), attention (items 11-20), and executive control (items 21-30). The maximum sub score for each domain is 40, yielding a total possible score of 120, where higher scores indicate greater perceived difficulties. While the original validation study by Arjomandnia et al. (2017) reported strong psychometric properties, including high internal consistency (Cronbach's α = .82 to .89 for subscales and total score) and established convergent validity with the Cornoldi questionnaire, the present study observed a slightly lower but acceptable reliability coefficient (α = .71). This discrepancy may be attributed to cross-cultural translation nuances or sample-specific characteristics. To ensure content validity for the current cultural context, the translated instrument underwent rigorous review and minor modifications by a panel of experts in psychology and education. Acknowledging the inherent limitations of self-report measures, such as potential response bias, future research could benefit from supplementing the WMQ with objective cognitive tasks to establish stronger convergent and discriminant validity for the adapted version.

Dennis and Vanderwaal Cognitive Flexibility Questionnaire (2009)

It is a 19-item self-report measure rated on a 7-point Likert scale. It assesses two core dimensions: problem-solving processing (13 items) and perception of controllability (6 items). Total scores range from 19 to 133, with higher scores indicating greater cognitive flexibility. The original validation and subsequent studies (e.g., Kahendani & Abul-Maali al-Husseini, 2017) have demonstrated strong psychometric properties for the CFI, reporting high internal consistency (α = .89 for total score, .78 for problem-solving, .81 for controllability). In the present study, the Persian version of the scale showed good content validity as confirmed by a panel of experts in psychology and education after necessary cultural adaptations. The reliability analysis yielded an acceptable Cronbach's alpha of .74 for the total scale, which, while slightly lower than the original validation, remains within an acceptable range for research purposes. This minor discrepancy may be attributed to cross-cultural translation challenges or sample-specific characteristics.

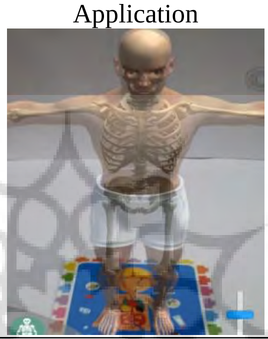
Augmented Reality-Based Training (ARBT) Program

The experimental group participated in a structured augmented reality-based training (ARBT) program, while the active control group received conventional instruction covering the same scientific material for an equivalent duration. This study design was implemented to control for potential confounding variables related to time, attention, and content exposure. The ARBT intervention was delivered over 10 sessions (25 minutes each), focusing on 5 core topics from the fifth-grade science textbook (Lesson 5: Body Movements, pp. 35-44). The training was administered using the Aramooz application (Version 2.3) installed on mobile devices. This application was selected for its ability to overlay interactive 3D models of anatomical structures (e.g., muscles, skeleton, vertebrae, brain, and spinal cord) onto the physical environment through the device's camera. In each session, students interacted with these models by rotating, zooming, disassembling, and reassembling them, and completing predefined interactive tasks (e.g., virtually labeling parts of a muscle, assembling a skeleton). The content and pedagogical structure of the ARBT program were validated for accuracy and age-appropriacy by a panel of 6 experienced fifth-grade science teachers. The active control group received traditional instruction on the same topics for the same duration (10 sessions, 25 minutes each). Their teaching utilized standard methods, including lectures using a whiteboard and marker, textbook reading, and note-taking with notebooks and pencils. No augmented reality technology was used in this group.

To conduct the research, written informed consent was obtained from the parents of all participating children. Before the commencement of the training sessions, a pre-test for assessing the working memory and cognitive flexibility was administered to both groups. Following the intervention period (ARBT for the experimental group and conventional teaching for the control group), all students were asked to fill out the working memory and cognitive flexibility questionnaires again as a post-test, according to their current views.

Table 1. Description of Training Sessions

Content	Session	Topics	Augmented Reality Training	Conventional Training
First	First and second	Muscles	Booklet - Mobile - Educational Application 	Notebook - Whiteboard - Marker - Lecture - Notebook - Pencil

Content	Session	Topics	Augmented Reality Training	Conventional Training
Second	Third and fourth	Skeleton	Booklet - Mobile - Educational Application 	Notebook - Whiteboard - Marker - Lecture - Notebook - Pencil
Third	Fifth and sixth	Vertebra	Booklet - Mobile - Educational Application 	Notebook - Whiteboard - Marker - Lecture - Notebook - Pencil
Fourth	Seventh and eighth	Brain and Spinal Cord	Booklet - Mobile - Educational Application 	Notebook - Whiteboard - Marker - Lecture - Notebook - Pencil
Fifth	Ninth and tenth	Final Summary	Booklet - Mobile - Educational Application	Notebook - Whiteboard - Marker - Lecture - Notebook - Pencil

After collecting the data, SPSS version 23 software was used to analyze the obtained data in two parts: descriptive analysis (frequency and frequency percentage) and inferential analysis (Kolmogrov-Smirnov and covariance).

Results

The descriptive demographic indicators of the study participants are shown in Table 2.

Table 2. Frequency and Percent of Gender and Age

Variables		f	%
Age	11 years old	27	75
	12 years old	9	25
Gender	Girl	18	50
	Boy	18	50

The results from Table 2 indicate that the frequency of indicators for 11-year-old children is higher than other indicators.

Prior to conducting inferential analyses, the assumptions of normality were assessed using the Kolmogorov-Smirnov test. As shown in Table 3, the significance values (*p*) for all variables at both pre-test and post-test were greater than .05, indicating that the data did not significantly deviate from a normal distribution. This supports the use of parametric statistical tests for subsequent analyses. Descriptive statistics (Means and Standard Deviations) are also presented in Table 3.

Table 3. Descriptive Statistics and Normality Test Results

Variable		stage		M	SD	Kolmogorov-Smirnov	
						Statistics	p
Working memory	Storage	Proof	Pretest	14.89	4.30	0.18	.12
			Posttest	15.94	4.18	0.17	.13
		Test	Pretest	14.50	4.12	0.18	.12
			Posttest	23.28	3.55	0.14	.20
	Attention	Proof	Pretest	15.33	3.91	0.19	.07
			Posttest	16.11	3.85	0.16	.20
		Test	Pretest	15.17	3.78	0.18	.12
			Posttest	22.06	3.21	0.15	.20
Cognitive flexibility	Executive control	Proof	Pretest	14.89	3.87	0.20	.38
			Posttest	15.12	3.79	0.24	.06
		Test	Pretest	15.11	3.65	0.20	.48
			Posttest	22.05	3.02	0.18	.12
	Problem-solving processing	Proof	Pretest	57.89	8.45	0.25	.06
			Posttest	59.17	8.30	0.18	.10
		Test	Pretest	58.61	8.12	0.18	.09
			Posttest	78.33	7.65	0.16	.19
	Perception of control	Proof	Pretest	26.39	4.25	0.15	.20
			Posttest	26.94	4.20	0.27	.09
		Test	Pretest	2683	4.11	0.19	.06
			Posttest	34.34	3.89	0.17	.14

As presented in Table 3, the mean scores of the control and experimental groups at pretest were very close on all variables, indicating successful random assignment and initial homogeneity of the groups. At posttest, the scores of the control group showed minimal change. In contrast, the experimental group showed significant improvement: significant increases in the scores of working memory performance and cognitive flexibility. The decrease in the standard deviation in the experimental group at posttest also indicates a more homogeneous and consistent response to the intervention.

Multivariate Analyses (MANCOVA)

To assess the overall effect of the intervention on the related components of each construct, two distinct one-way multivariate analyses of covariance (MANCOVAs) were performed, with pre-test scores included as covariates.

Table 4. Results of Separate MANCOVAs for Component Sets

Construct & Effect		Value	f	df. Hypothesis	df. Error	p	partial η^2
Pillai's Trace	Working Memory Performance	0.85	58.74	3	31	.001	0.85
	Cognitive Flexibility	0.80	64.15	2	32	.001	0.80

The MANCOVA for the combined working memory components revealed a statistically significant effect of the intervention, *Pillai's Trace* = .85, F= 58.74, $p<.001$, with a very large effect size (partial η^2 = .85). Similarly, the MANCOVA for the combined cognitive flexibility components also showed a significant effect, *Pillai's Trace* = .80, F= 64.15, $p<.001$, with a very large effect size (partial η^2 = .80).

Analyses of Covariance for Total Scores

To examine the effect on the overall, total scores of each construct, two one-way analyses of covariance (ANCOVAs) were performed, using the pre-test total scores as covariates.

Table 5. Results of ANCOVAs for Total Scores

Test Name	f	df	p	partial η^2
Total Working Memory Performance	120.45	1	.001	0.78
Total Cognitive Flexibility	125.88	1	.001	0.79

The ANCOVA results confirmed a statistically significant effect of the Augmented Reality-Based Training on both the total working memory score, F= 120.45, $p<.001$, partial η^2 = .78, and the total cognitive flexibility score, F= 125.88, $p<.001$, partial η^2 = .79. The effect sizes were large.

Follow-up Univariate Analyses

Following the significant MANCOVA results, a series of one-way analyses of covariance (ANCOVAs) were conducted as follow-up tests on each dependent variable, using the respective pre-test scores as covariates. The results of these analyses are fully detailed in Table 6.

Table 6. Results of Follow-up ANCOVAs for Each Component

Source	Dependent Variable		SS	df1	MS	F	p	partial η²
Pre-test (Covariate)	Working Memory	Storage	1250.50	1	1250.50	150.25	.001	0.82
		Attention	1210.75	1	1210.75	145.60	.001	0.82
	Cognitive Flexibility	Executive Control	1180.30	1	1180.30	138.75	.001	0.81
		Problem Solving Processing	1450.80	1	1450.80	165.30	.001	0.83
		Perceived Controllability	1350.20	1	1350.20	155.10	.001	0.82
Group (Effect)	Working Memory	Storage	920.40	1	920.40	110.50	.001	0.77
		Attention	960.20	1	960.20	115.25	.001	0.78
	Cognitive Flexibility	Executive Control	880.15	1	880.15	105.75	.001	0.76
		Problem Solving Processing	1090.65	1	1090.65	130.10	.001	0.80
		Perceived Controllability	985.30	1	985.30	118.35	.001	0.78
Error	Working Memory	Storage	275.05	33	8.33			
		Attention	274.87	33	8.33			
	Cognitive Flexibility	Executive Control	274.50	33	8.32			
		Problem Solving Processing	276.95	33	8.39			
		Perceived Controllability	275.80	33	8.36			
Total	Working Memory	Storage	9875.45	35				
		Attention	9865.42	35				
	Cognitive Flexibility	Executive Control	9855.25	35				
		Problem Solving Processing	9950.75	35				
		Perceived Controllability	9925.60	35				

The ANCOVA models confirmed that the pre-test covariate was a significant predictor of the post-test scores for all variables (all $p<.001$). After controlling for the effect of the pre-test scores, there was a statistically significant main effect of the intervention (Group) on all dependent variables (all $p<.001$). Specifically, the effect of the intervention on the working memory performance components was as follows: Storage, $F= 110.50$, $p<.001$, partial $\eta^2 = .77$; Attention, $F= 115.25$, $p<.001$, partial $\eta^2 = .78$; and Executive Control, $F= 105.75$, $p< .001$, partial $\eta^2 = .76$. The intervention's effect on the cognitive flexibility components was also significant: Problem-Solving Processing, $F= 130.10$, $p< .001$, partial $\eta^2 = .80$; and Perception of Controllability, $F= 118.35$, $p< .001$, partial $\eta^2 = .78$.

Discussion

This study investigated the effectiveness of Augmented Reality-Based Training (ARBT) on working memory performance and cognitive flexibility in children. The findings revealed that the ARBT intervention exerted a significant positive effect on children's working memory, enhancing storage capacity, attentional control, and executive functioning. These results align with prior research by Supli and Yan (2024), Lim et al. (2023), Ibáñez et al. (2015), and Knapp et al. (2019), confirming the positive impact of ARBT on working memory.

Augmented Reality-Based Training (ARBT) fosters intrinsic motivation that profoundly enhances children's learning capacity and facilitates daily activities. Its implementation in educational contexts generates engaging experiences that support information retention during task execution. Through this approach, children become familiar with diverse digital tools and methods for collecting, organizing, and presenting information, thereby strengthening their ability to select, structure, and implement acquired knowledge. By creating rich visual-verbal learning environments, Augmented Reality supports optimal information organization in children's minds. During learning activities, it enhances self-monitoring capabilities and enables metacognitive evaluation of cognitive processes. The diverse learning objects in Augmented Reality-Based Training (ARBT) facilitate children's learning progression, and through improved information processing, their working memory performance advances significantly. Furthermore, Augmented Reality-Based Training (ARBT) systematically structures information through integrated short-term and long-term memory systems. This consolidation in long-term memory ultimately enhances working memory performance in children.

Findings further demonstrated that Augmented Reality-Based Training (ARBT) significantly enhanced children's cognitive flexibility, improving both problem-solving processing and perception of controllability. These results are consistent with those ofy Jeter et al. (2018) and Frankazino and Felsner (2015), confirming Augmented Reality's positive impact on cognitive flexibility. Augmented Reality engages multisensory pathways during instruction, enabling simultaneous management of multiple task dimensions. It fosters independence and critical thinking while building learners' confidence in accessing information and developing learning strategies. This prepares individuals to consciously and precisely adapt their approaches when redirecting goals. Through educational simulations, Augmented Reality creates authentic, immersive experiences that heighten environmental awareness and adaptability. Its core strength lies in delivering learning flexibility, enhancing children's capacity to adjust to instructional variations. Augmented Reality also strengthens peer connections, promoting behavioral adaptability essential for integrating diverse perspectives. By constructing knowledge through social interactions, Augmented Reality increases children's ability to respond to daily personal challenges—a hallmark of cognitive flexibility. Collectively, this approach substantially impacts self-efficacy, learning motivation, problem-solving autonomy, academic self-sufficiency, and sustained attention, all critical for developing robust cognitive flexibility.

Conclusion

The robust findings of this study, demonstrating significant enhancements in working memory (storage, attention, executive control) and cognitive flexibility (problem-solving, controllability) through Augmented Reality-Based Training (ARBT), can be cogently interpreted through established theoretical frameworks. The efficacy of ARBT in creating interactive and multisensory learning environments is fundamentally supported by Mayer's Cognitive Theory of Multimedia Learning and the embodied cognition perspective. ARBT effectively utilizes dual channels (visual and auditory) for processing information, minimizes extraneous cognitive load, and fosters generative processing by requiring physical interaction with virtual content, leading to deeper encoding and superior knowledge construction compared to traditional passive methods (Mayer, 2009; Varela et al., 1991). This active participation is not merely engaging but is a critical driver of neurocognitive plasticity, facilitating the integration of information into long-term memory through mechanisms described in Hebbian theory—where repeatedly activated neural pathways are strengthened "cells that fire together, wire together" (Hebb, 1949). Furthermore, the role of ARBT in stimulating intrinsic motivation is explained by Self-Determination Theory (Ryan & Deci, 2000).

The technology's immersive nature directly satisfies the core psychological needs for autonomy (by offering choice and exploration), competence (through scaffolded challenges and immediate feedback), and relatedness (via shared, collaborative experiences), which are essential for fostering sustained engagement and self-regulated learning. The transfer of these cognitive benefits to academic domains like social sciences and Persian is theorized through the lens of far transfer and executive function training. By consistently challenging and improving core cognitive skills like updating (in working memory), shifting (in cognitive flexibility), and inhibition within an engaging context, ARBT enhances the underlying neural infrastructure. This, in turn, can improve performance in unrelated tasks that rely on the same executive resources, a concept supported by modern process-based training frameworks (Diamond & Ling, 2016). Therefore, integrating AR into curricula with a focus on self-awareness and well-being is not just an application of technology; it is a theoretically-grounded strategy to systematically enhance the brain's executive functions and prepare children with the cognitive agility necessary to navigate complex, dynamic environmental challenges.

This study has several limitations that must be acknowledged to properly contextualize its findings. First, the exclusive reliance on self-report questionnaires for data collection introduces the potential for social desirability bias and common method variance, which may have inflated the observed relationships between variables. While these instruments demonstrated acceptable reliability, they cannot capture the full complexity of cognitive processes as objectively as behavioral tasks or physiological measures might. Second, the geographical restriction to Aqqala County and sampling from a single grade level significantly limits the generalizability of the results. The cultural, socioeconomic, and educational characteristics of this specific population may not represent the broader diversity of children across different regions and developmental stages. Third, the modest sample size of the participants, though sufficient for detecting large effects, limits the statistical power for conducting more complex analyses and increases the vulnerability to Type I errors. Fourth, the study did not control for potential confounding variables such as parental socioeconomic status, prior technology exposure, or individual differences in baseline cognitive ability, which could have influenced the outcomes. Finally, the lack of a long-term follow-up assessment prevents any conclusions about the durability of the observed effects beyond the immediate post-test period. Moreover, sole reliance on self-report measures presents a potential limitation due to inherent response biases. Future studies using this adapted version would benefit from establishing its convergent and discriminant validity through correlation with objective behavioral tasks or other established cognitive assessments.

To address these limitations and build upon the present findings, future research should pursue several avenues. Methodologically, subsequent studies should employ multimodal assessment strategies that combine self-report measures with objective cognitive tasks (e.g., n-back for working memory, task-switching paradigms for cognitive flexibility) and potentially neurophysiological indicators (e.g., EEG, fNIRS) to triangulate findings and enhance validity. Empirically, research must expand to include larger, more diverse samples spanning multiple grade levels, socioeconomic backgrounds, and geographical regions to establish the external validity and cross-cultural applicability of ARBT's effects. Theoretically, investigations should aim to unpack the mechanisms of action by measuring potential mediators (e.g., intrinsic motivation, cognitive engagement, situational interest) to test the proposed theoretical pathways through which AR influences cognition. Furthermore, longitudinal designs with multiple follow-up assessments are crucial to determine the long-term retention of training benefits and their transfer to academic achievement and real-world functioning. Finally, practical research should focus on developing and evaluating teacher-training frameworks that equip educators with the necessary pedagogical content knowledge to effectively integrate AR into curricula—not as a gadget, but as a tool to strategically foster self-awareness, psychological well-being, and cognitive skills within subjects like social sciences and language arts.

Author Contributions

All the authors participated in the design, implementation, and writing of all parts of this research.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The authors obtained a written consent from all participants' parents and ensure them that the data will be exclusively used for research purposes.

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Conflict of interest

There are no conflicts of interest.

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