# Augmented reality and memory functions: An experimental study in primary school

## Realtà aumentata e funzioni mnestiche: uno studio sperimentale nella scuola primaria

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**ABSTRACT** The research project explores the integration of Augmented Reality (AR) into educational practices to enhance student learning. Previous studies conducted in university settings have demonstrated AR's effectiveness in supporting content comprehension. This study aims to investigate whether similar benefits can be observed in primary school, with a specific focus on strengthening memory functions. The six-month intervention was implemented in a third-grade classroom, where AR was integrated into history lessons. The results show a significant improvement in content acquisition (H1), as well as in visuospatial memory (H2) and semantic memory (H3). The most notable effects were found in the memory-related components, suggesting that AR may facilitate cognitive processes involved in information encoding and retrieval, even at an early developmental stage. Although the intervention is not formally designed as cognitive training, the findings reveal its potential to support the development of memory skills in young learners. Further studies are needed to explore these implications across different.

**SOMMARIO** Il progetto di ricerca esplora l'integrazione della realtà aumentata (AR) nella didattica per migliorare l'apprendimento degli studenti. Precedenti ricerche condotte in contesti universitari hanno evidenziato

l'efficacia dell'AR nel supportare la comprensione dei contenuti. Questo studio si propone di verificare se tali benefici siano osservabili anche nella scuola primaria, concentrandosi in particolare sul potenziamento di alcune funzioni mnemoniche. L'intervento, della durata di sei mesi, è stato implementato in una classe terza della scuola primaria, dove la realtà aumentata è stata integrata nelle lezioni di storia. I risultati indicano un miglioramento significativo nell'acquisizione dei contenuti (H1), nonché nella memoria visuo-spaziale (H2) e semantica (H3). Gli effetti più marcati si registrano nelle componenti mnemoniche, suggerendo che l'AR possa favorire processi cognitivi legati alla codifica e al recupero delle informazioni, anche in età evolutiva. Sebbene non sia formalmente configurato come un training cognitivo, l'intervento mostra un potenziale rilevante per il supporto allo sviluppo delle abilità di memoria nei bambini. Saranno necessari studi futuri per esplorare ulteriormente queste implicazioni in contesti educativi differenti.

## 1. Introduction

Over the past two decades, growing interest in immersive technologies has opened new perspectives for educational innovation. In particular, Augmented Reality (AR) has emerged as one of the most promising tools for enriching learning environments and fostering interactive, multisensory, and customizable instruction (Akçayır & Akçayır, 2017; Billinghurst & Dunser, 2012). AR allows digital content to be superimposed onto the physical world, promoting a cognitive experience that simultaneously stimulates perception, attention, and memory, while encouraging active and constructive learning (Ibáñez & Delgado-Kloos, 2018; Jang et al., 2021).

Several studies have shown that the use of AR in educational contexts enhances the understanding of complex concepts, especially through the interactive manipulation of 3D objects, and improves student engagement and motivation (Radu, 2014; Lembo et al., 2024). This positive effect appears particularly evident in higher education settings, where most experiments have been conducted. However, as Garzón and Acevedo (2019) pointed out, the use of AR in primary education remains underexplored: their meta-analysis reveals a strong predominance of studies targeting university students, leaving a significant gap across a broad segment of the educational system. This imbalance represents a notable gap in the literature, especially considering that childhood is a critical stage for cognitive development and the formation of learning processes.

The interest in applying AR to early education is supported by recent theoretical perspectives such as embodied cognition (Wilson, 2002), which asserts that learning emerges from bodily interaction with the environment, and situated learning (Brown et al., 1989), which emphasizes immersive and meaningful learning contexts. Within this framework, technologies like AR offer unique opportunities to support active knowledge construction through sensorimotor interaction, promoting multimodal encoding of information and more effective memory consolidation (Dede, 2009).

This study aligns with this trajectory, aiming to evaluate the effectiveness of augmented reality applied to teaching, previously tested in university settings, within a new age group: primary school students. Specifically, the project seeks to explore the impact of AR on the

learning of historical content, with particular focus on three areas: content comprehension (H1), semantic memory (H2), and visuospatial memory (H3). The objective is to assess whether, even in childhood, an augmented learning environment can enhance the acquisition of knowledge.

## 1.1. Innovative Learning Environment: AR applied in Didactics

Today, when discussing learning environments, it is no longer sufficient to focus solely on theoretical knowledge; rather, it has become increasingly essential to emphasise the concreteness and applicability of acquired knowledge. In this perspective, AR emerges as a key component, becoming an integral part of the educational environment and offering new possibilities for interaction and experimentation. A modern learning environment must evolve in parallel with technological innovation, adapting to the needs of digitally native students who are accustomed to increasingly dynamic and interactive learning methods.

Within this framework, AR stands out for its educational potential, allowing students to engage in immersive experiences that foster a high level of interaction with the knowledge they need to acquire (Tomassoni, 2021). Recent applications of AR in textbooks, which enhance their functionalities (Cino, 2017; Filomia, 2019), highlight the need for a broader reflection on the psycho-pedagogical potential that digital technologies can offer in educational contexts (Diegmann et al., 2015; Niewint et al., 2019; Panciroli & Macauda, 2018).

The use of AR enhances teaching by making content presentation more effective and engaging. Unlike traditional tools such as slides, images, or video files, AR enables students to interact actively with concepts, overcoming the limitations of passive learning and rendering the experience more dynamic and immersive (Tomassoni, 2021). This direct interaction with content has led to a re-evaluation of teaching methods based on two fundamental principles: adapting to the new learning habits of students, who now operate in predominantly digital environments, and leveraging the potential of Embodied Cognition, which posits that the body serves as the most natural channel for learning (Gomez Paloma, 2017).

AR not only provides access to content but also allows for its manipulation, fostering greater awareness and control over one's learning process. This results in an improvement in learning quality, thanks to increased active participation and a greater ability to process and internalise information compared to traditional methods based on static images. One of the most innovative aspects of AR is its ability to simultaneously activate multiple senses, transforming the educational experience into a multisensory and holistic learning process that engages the entire body. This approach not only supports personalised learning based on different cognitive styles but also effectively addresses the educational needs of students with disabilities, offering a more inclusive and accessible learning environment (Di Martino & Longo, 2019).

In conclusion, AR represents an extraordinary opportunity for the field of education, redefining the way students interact with knowledge and paving the way for new, more interactive, inclusive, and stimulating teaching methodologies.

## 1.2. Augmented Reality for Memory Systems

Over the past decade, research has demonstrated how AR provides significant benefits to memory systems, proving to be a valuable support for education (Juan et al., 2014; Lim & Lim, 2020; Rosello et al., 2016). One of the most relevant effects of AR on memory concerns sensory engagement. By integrating visual, auditory, and even tactile elements, this technology simultaneously stimulates multiple senses, creating a multisensory experience that facilitates a more effective memorisation process (Han et al., 2021). Real-time interaction and hands-on

experience with three-dimensional objects enhance memory retention, assisting students in understanding fundamental concepts, reducing cognitive load, and strengthening their learning abilities (Altmeyer et al., 2020; Singh et al., 2019).

Recent studies have highlighted AR's role in enhancing cognitive functions, demonstrating how this technology can contribute to the development of working memory, reinforcement of attentional processes, and improvement of mnemonic abilities, particularly regarding visual and visuospatial memory (İbili, 2019; Larchen Costuchen et al., 2021). It is hypothesised that the combined activity of observation and interaction with these models may stimulate a greater number of neural networks, facilitating the comprehension of key information and concepts (Buchner et al., 2022; Squires, 2017). Additionally, AR enables the creation of immersive experiences that integrate digital information with the physical environment, promoting greater contextualisation of learning. By associating information with specific virtual scenarios or interactive visual elements, this technology capitalises on the brain's natural predisposition to connect data with spatial contexts, thereby enhancing associative memory (Squires, 2017; Tomassoni, 2021).

In particular, studies by Juan et al. (2014) and Ponce et al. (2024) have highlighted how the use of AR can lead to a significant improvement in visuospatial memory, understood as the ability to perceive, process, and manipulate mental representations based on spatial coordinates. This skill enables students to identify and assess spatial relationships between themselves and surrounding objects, as well as among the objects themselves, fostering a greater awareness of orientation and the arrangement of visual stimuli.

## 2. Theoretical Framework

Digital innovation has redefined the educational landscape, necessitating a multidisciplinary approach that integrates established pedagogical principles with advanced technologies. In this context, the present study explores the effectiveness of Augmented Didactics/ATENA, a methodology that combines the paradigms of constructivism, embodied cognition, and ubiquitous learning fostering a more engaging, personalised, and accessible learning experience (Gomez Paloma, 2017; Nino, 2023). The constructivist approach (Piaget & Inhelder, 2008; Vygotsky, 1978) emphasizes the active role of the learner in building knowledge through direct experience and meaningful interaction with content. AR, as an interactive and immersive technology, allows students to explore educational content in an autonomous and personalized way, making learning more experiential and concrete. Furthermore, the integration of familiar digital tools, such as tablets or smartphones, aligns with the cultural environment of digital-native students, fostering a connection between technological mediation and the learner's socio-cognitive context. This strengthens the educational relevance of AR as a tool capable of enhancing motivation and active engagement, thanks to the proximity between learning modalities and students' everyday practices.

Ubiquitous learning is defined as a continuous and pervasive learning environment, supported by mobile devices, integrated computers, and wireless networks, naturally embedded into daily life (Aljawarneh, 2020). Its primary objective is to offer students content and interaction opportunities anytime and anywhere (Hwang et al., 2012). This learning approach integrates real-world experiences with virtual information, dynamically adapting to learners' needs and their surrounding contexts.

Learning in a ubiquitous environment is characterised by highly personalised interaction with content, activities, and the learning system, as well as with other participants, including teachers and peers (Cárdenas-Robledo & Peña-Ayala, 2018). This adaptation is based on key factors such as the learner's current educational objectives, interests, preferences, cognitive characteristics, learning history, and level of expertise in a specific domain. Furthermore, the physical and technological context of learning plays a crucial role: personalisation considers environmental characteristics, situational needs, available technological mediators, and the situational context of the educational activity.

The paradigm of ubiquitous learning (Hwang et al., 2012) emphasizes the possibility of accessing educational content anytime and anywhere, thanks to the widespread availability of mobile devices. Augmented educational content, designed to be used via smartphones and tablets, provides students with continuous and customizable access to learning resources, freeing education from the spatial and temporal constraints of traditional classroom instruction. This ubiquitous dimension enhances students' autonomy and encourages individual responsibility in their learning journey, offering a flexible educational experience tailored to different cognitive styles and learning needs. At the same time, embodied cognition highlights the role of the body as a key element in learning: direct manipulation of virtual content enables students to activate deeper cognitive processes, improving comprehension and retention of information (Shapiro & Stolz, 2019). According to the paradigm of embodied cognition, learning is not merely an abstract mental activity, but involves the body and physical interaction with the environment (Gomez Paloma, 2017; Shapiro & Stolz, 2019; Wilson, 2002). In this context, the use of AR through mobile devices (such as tablets and smartphones) enables students to directly manipulate 3D models, for instance, through gestures like zooming, rotating, and dragging on the screen, promoting a multisensory learning experience deeply integrated with bodily action. This type of interaction enhances cognitive processing, improving both the understanding and retention of the presented concepts. The personalised access to educational content, free from spatial and temporal constraints, allows the learning pathway to be tailored to individual needs, fostering student autonomy and metacognitive awareness.

In summary, this methodology, based on the use of augmented reality, integrates these three theoretical paradigms in a synergistic way: it fosters experiential and embodied learning (embodied cognition), enables the active construction of knowledge consistent with students' digital culture (constructivism), and supports the continuity and accessibility of the educational experience (ubiquitous learning).

## 3. ATENA: from 3D model to AR

The technical and technological aspects of this project, developed in collaboration with the Department of Engineering, materialise in the creation of three-dimensional models for educational purposes using GLTF-format files. This format provides the advantage of including a comprehensive scene description in JSON, incorporating detailed information on node hierarchy, cameras, materials, animations, and meshes. The 3D models are retrieved from a repository via JavaScript scripts and linked to ArUco markers, versatile elements that can be utilised across various digital and physical contexts, such as web pages, presentations, PDF documents, or printed materials.

One of the distinguishing features of ArUco markers is their ease of detection through smartphone cameras, even when the acquisition angle is high or when the marker is rotated

relative to the device's vertical position. Due to their binary encoding, these markers offer increased robustness in detection, enabling error correction during the decoding process. On mobile platforms, students can manipulate the 3D model using touchscreen commands, generating an effect that seamlessly integrates the model into the immediate reality, reinforcing the perception of an immersive AR experience, perfectly aligned with the time and space of the study session.

The adoption of ArUco markers proves particularly suitable for students due to their resistance to perspective distortions and rotations, maintaining effectiveness even under low-light conditions. This ensures that the AR experience remains accessible regardless of the environment or time of day, facilitating usability and research accessibility. Furthermore, given the varied positions of students during lessons, where perpendicular alignment between the device and the physical support is not always guaranteed, these markers provide an effective solution to overcome potential difficulties, fully meeting the objectives of the project.

From a theoretical perspective, the integration of embodied cognition allows for overcoming the Cartesian mind-body dualism, restoring a central role to the body in learning processes. This necessitates making the AR experience engaging on multiple levels by offering interactive models with scalability and rotation functionalities, activated through touchscreen gestures. The ability to directly manipulate virtual content enhances information acquisition, fostering a more experiential and immersive learning process.

Supporting this experience is the use of the Aframe framework, which facilitates the manipulation of 3D models, enabling their overlay onto the student's physical reality. This approach not only increases the user's emotional engagement but also transforms the student into an active participant in the learning process, promoting deeper internalisation of concepts through an educational experience anchored in their surrounding reality.

# 4. Research Project

This study represents a new phase of the ATENA research project, in which AR has been progressively integrated into educational contexts. Building upon prior findings obtained with university students, the present research shifts the focus to a younger population, aiming to investigate the applicability and effects of the same methodology in a primary school setting. Specifically, AR-based content was embedded within textbooks and classroom practices, with the goal of evaluating its impact on two levels: first, in terms of children's memory and comprehension of curricular content; second, in terms of the broader potential of the ATENA methodology as a tool for strengthening general memory processes through extended use in early education.

## 4.1. Research Hypothesis

In this study, three research hypotheses are proposed:
- H1: The integration of AR into primary school teaching enhances content acquisition.
- H2: The prolonged use of the ATENA teaching methodology improves visuospatial memory in primary school children.
- H3: The prolonged use of the ATENA teaching methodology strengthens semantic memory in primary school children.

## 4.2. Sample

The study was conducted on a convenience sample of 26 children (13 males, 13 females) enrolled in a third-grade classroom of a public primary school in Rome, Italy. Participants were aged between 8 and 9 years ($M$ = 8.30, $SD$ = 0.45). The majority of the students (n = 24) were Italian nationals, whereas two students were of non-Italian origin and had resided in Italy for more than five years, ensuring full exposure to the Italian language and educational system. One participant had a certified diagnosis of Autism Spectrum Disorder (ASD). No additional neurodevelopmental or learning disorders were reported.

## 4.3. Tools and Methods

The experiment initially involved the creation of AR educational content related to the subject of history. In a second phase, QR codes and Aruco markers were embedded in the educational materials so that they could be viewed both during lessons and independently during home study. Before proceeding with the start of the experiment, authorization was requested from the school and the teachers to conduct the project during school hours, and informed consent was obtained from each child's parent. During data processing, each child was assigned a code to ensure user anonymity.

From November 2023 to April 2024, for two hours a week, the children attended history lessons using AR, which was accessible through tablets provided by the school (Figure 1).



**Figure 1.** Children using AR during lessons.

The researchers trained the history teacher on how to conduct the educational methodology and were present in the classroom at the beginning of the experiment to provide technological and technical support. Subsequently, the lessons were conducted entirely independently by the teacher, who followed her traditional teaching approach, incorporating only the use of AR.

The assessment was conducted at T0, in October 2023 before the start of the experiment, and at T1 in May, at the conclusion of the experiment.

For H1, an ecological approach was adopted by analysing the regular curricular assessments carried out by the classroom teacher over the course of the academic year. The comparison focused on assessments related to topics taught prior to the introduction of AR and those addressed after its integration. Importantly, the tests used for this analysis consisted of

standardised written exams featuring nine multiple-choice questions and one open-ended question, all graded on a 0–10 scale. Given that multiple-choice questions allow for objective scoring based on unambiguous correct answers, the risk of observer bias was minimised. The decision to rely on the teacher's established evaluation procedures further preserved the ecological validity of the study, ensuring the assessments reflected authentic learning conditions without introducing artificial testing formats.

For H2, the M3 test from the standardised NEPSY-II battery was selected, specifically designed to assess visuospatial memory in children. This test evaluates the ability to encode, retain, and recall spatial information presented visually, measuring both short-term visuospatial memory and the capacity to accurately reproduce the position of visual stimuli within a defined space. The administration involves presenting a series of visual configurations that the child must observe and subsequently reproduce, following a standardised protocol. The duration of the test varies depending on the participant's age and response speed but is typically completed within 10-15 minutes.

For H3, the M4 test from the standardised NEPSY-II battery was chosen, as it is specifically designed to assess semantic memory in children. This test measures the ability to learn, recall, and recognise verbal information, evaluating both short-term memory and the long-term retention of semantic concepts. The administration involves presenting a set of verbal stimuli that the child must memorise and subsequently recall or recognise in different contexts, following a standardised protocol. The execution time varies according to the child's age and responses but generally takes approximately 10-15 minutes to complete.

In order to perform the statistical analyses, JAMOVI software (version 2.3.28) was used.

## 4.4. Results

### 4.4.1.     H1 – Curricular assessment

The following section presents the results obtained from the pre- and post-AR assessment tasks for the verification of H1 (Figure 2).
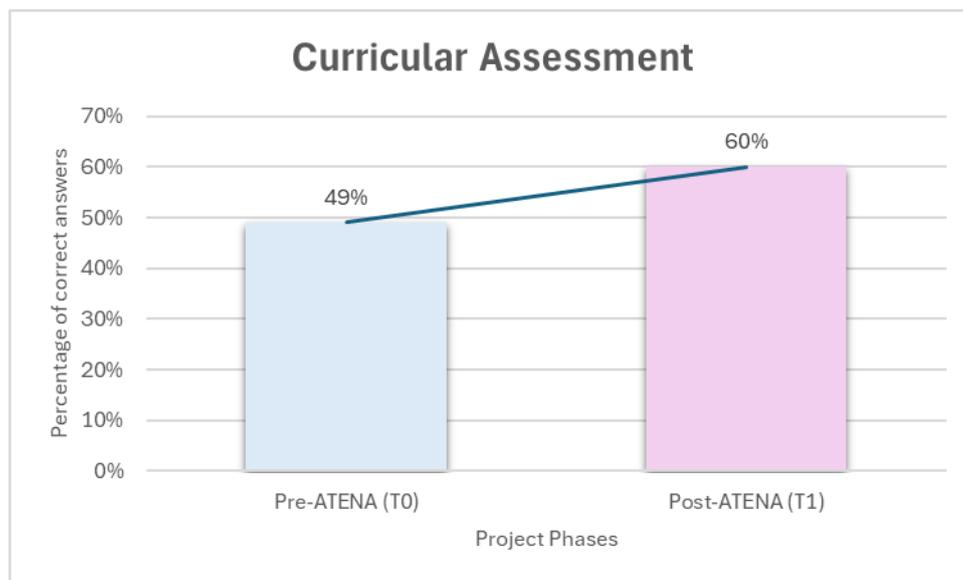
**Figure 2.** Curricular Assessment.

Figure 2 presents the results obtained from the comparison between pre-ATENA and post-ATENA assessments. Specifically, the analysis focused on test scores related to educational content delivered without AR and with AR. To ensure comparability, the average score was calculated from three assessments administered before the introduction of AR and three assessments, with identical structure and characteristics, conducted with the integration of AR. The results indicate a significant improvement in the retention of educational stimuli, with 49% correct responses in the pre-phase increasing to 60% in the post-phase, reflecting an overall 11% improvement attributable to the use of AR.

### 4.4.2. H2 – Visuo-spatial Memory

The following section presents the results obtained from the pre- and post-AR assessment tasks for the verification of H2 (Figure 3).
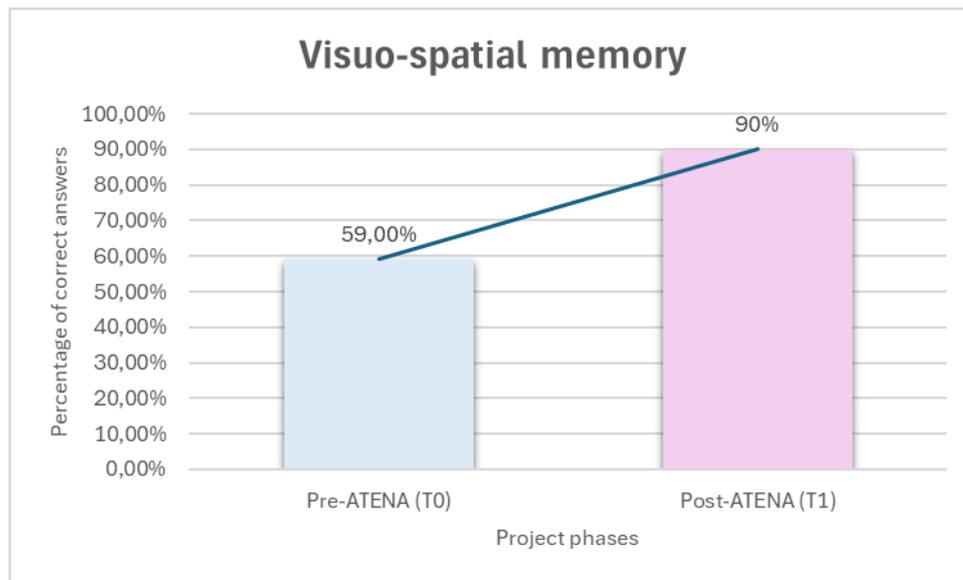
**Figure 3.** Visuo-spatial Memory.

Figure 3 presents the results obtained from the M3 test of the NEPSY-II battery, specifically designed to assess visuospatial memory. As shown, participants exhibited a 59% retention level in the pre-ATENA phase, which increased to 90% in the post-ATENA phase, resulting in a 31% improvement rate.

### 4.4.3. H3 – Semantic Memory

The following section presents the results obtained from the pre- and post-AR assessment tasks for the verification of H3 (Figure 4).
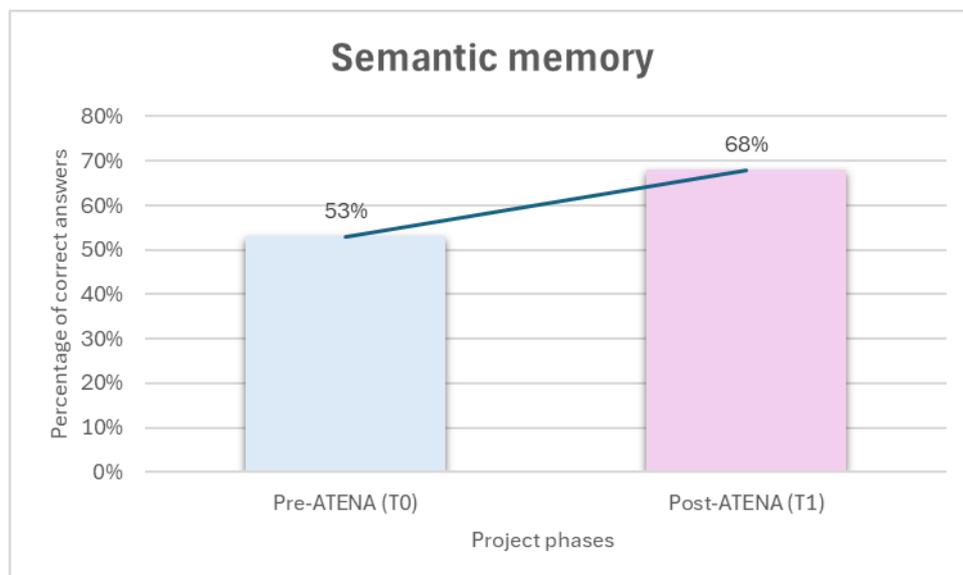


**Figure 4.** Semantic Memory.

Figure 4 presents the results related to the assessment of semantic memory ability. Specifically, the graph displays the outcomes obtained from the M4 test of the NEPSY-II battery. The data indicate that while in the pre-ATENA phase, the sample exhibited a 53% level of retention, in the post-ATENA phase, retention increased to 68%, reflecting a 15% improvement.

### 4.5. Data analysis

#### 4.5.1. H1 – Curricular Assessment

The descriptive statistics of the variables under examination (H1) are provided below (Table 1).

**Table 1.** H1 Descriptives.

| Descriptives | Pre-ATENA | Post-ATENA |
|---|---|---|
| N | 78 | 78 |
| Missing | 0 | 0 |
| Mean | 4.8 | 6.0 |
| Median | 4.5 | 5.7 |
| Standard deviation | 3.07 | 2.91 |
| Minimum | 3 | 4 |
| Maximum | 8 | 10 |
| Shapiro-Wilk W | .9416 | .9488 |
| Shapiro-Wilk p | .0014 | .0034 |

Table 1, which presents the descriptive statistics related to students' curricular test scores, highlights the presence of 78 observations for each phase of the experiment, derived from the inclusion of three tests per participant, with no missing values. Additionally, the Shapiro–Wilk test indicated significant deviations from normality for both the pre-ATENA phase ($W = .942$, $p = .0014$) and the post-ATENA phase ($W = .949$, $p = .0034$). However, the distribution of the difference scores did not significantly deviate from normality ($p > .05$), thereby satisfying the assumption required for the paired-samples $t$ test. Table 2 presents the results of the paired-samples t-test conducted to test H1.

**Table 2.** H1 Paired sample t test.

| Statistics | df | p | Effect size | |
|---|---|---|---|---|
| 2.77 | 77 | < .001 | Cohen's d | 0.31 |

The paired-samples $t$ test revealed a statistically significant difference between the pre- and post-intervention measurements, $t(77) = 2.77$, $p = .007$, $d = 0.31$. The effect size indicates a small magnitude of the intervention effect. Therefore, H1 was supported.

### 4.5.2.    H2 – Visuo-spatial Memory

The descriptive statistics of the variables under examination (H2) are provided below (Table 3).

**Table 3.** H2 Descriptives.

| Descriptives | Pre-ATENA | Post-ATENA |
|---|---|---|
| N | 26 | 26 |
| Missing | 0 | 0 |
| Mean | 5.9 | 9.0 |
| Median | 5.4 | 8.8 |
| Standard deviation | 2.1 | 0.9 |
| Minimum | 2 | 4 |
| Maximum | 9 | 10 |
| Shapiro-Wilk W | .987 | .878 |
| Shapiro-Wilk p | .997 | .854 |

Table 3 presents the descriptive statistics for the M3 test, which assesses children's visuospatial memory. The dataset comprises 26 observations per phase, with no missing data. The Shapiro–Wilk test indicated no significant deviation from normality in either the pre-ATENA phase ($W = .987$, $p = .997$) or the post-ATENA phase ($W = .878$, $p = .854$), thus supporting the assumption of normality.

Table 4 presents the results of the paired-samples t-test conducted to test H2.

**Table 4.** H2 Paired sample t test.

| Statistics | df | p | Effect size | |
|---|---|---|---|---|
| 7.80 | 25 | < .001 | Cohen's d | 1.95 |

The paired-sample t-test (Table 4) revealed a statistically significant difference between the pre- and post-training measurements, $t(25) = -7.80$, $p < 0.001$. The effect size analysis indicated a Cohen's d of 1.95, suggesting a large effect. These results indicate that the intervention had a substantial impact on participants' performance, demonstrating a strong improvement following the training. H2 was supported.

### 4.5.3.    H3 – Semantic Memory

The descriptive statistics of the variables under examination (H3) are provided below (Table 5).

**Table 5.** H3 Descriptives.

| Descriptives | Pre-ATENA | Post-ATENA |
|---|---|---|
| N | 26 | 26 |
| Missing | 0 | 0 |
| Mean | 5.3 | 6.8 |
| Median | 5.0 | 6.4 |
| Standard deviation | 2.3 | 1.5 |
| Minimum | 1 | 2 |
| Maximum | 7 | 8 |
| Shapiro-Wilk W | .976 | .851 |
| Shapiro-Wilk p | .750 | .996 |

Table 5 presents the descriptive statistics for the M4 test, which assesses children's visuospatial memory. The dataset comprises 26 observations per phase, with no missing data. The Shapiro–Wilk test indicated no significant deviation from normality in either the pre-ATENA phase ($W = .976$, $p = .750$) or the post-ATENA phase ($W = .851$, $p = .996$), thereby supporting the assumption of normality.

Table 6 presents the results of the paired-samples t-test conducted to test H3.

**Table 6.** H3 Paired sample t-test.

| Statistics | df | p | Effect size | |
|---|---|---|---|---|
| 5.31 | 25 | < .001 | Cohen's d | 1.42 |

The paired-sample t-test (Table 6) revealed a statistically significant difference between the pre- and post-training measurements, t(25) = 5.31, p < .001. The effect size analysis indicated a Cohen's d of 1.42, suggesting a large effect. These results indicate that the intervention had a substantial impact on participants' performance, leading to a marked improvement following the ATENA training.

## 4.6. Discussion

The results of this study provide empirical support for the pedagogical potential of AR when integrated into traditional teaching practices at the primary school level, in line with the theoretical frameworks of embodied cognition, constructivism, and ubiquitous learning.

With respect to Hypothesis H1, the analysis of curricular assessments revealed an 11% improvement between the pre-ATENA and post-ATENA phases, with a small but meaningful effect size (Cohen's d = 0.31). Although the tests were part of the teacher's standard evaluation routine, their structure, based on multiple-choice and open-ended questions, allowed for objective data collection within an authentic educational setting. These findings confirm that AR, by making content more interactive and immersive, can enhance students' understanding and retention of historical knowledge. This aligns with constructivist principles, which emphasize the learner's active role in constructing meaning through direct engagement with educational materials (Piaget & Inhelder, 2008; Vygotsky, 1978). By interacting with digital reconstructions of historical events, students moved beyond passive reception and engaged in

situated, experiential learning. Additionally, the possibility of accessing AR content outside of class time using tablets or smartphones reflects the logic of ubiquitous learning (Hwang et al., 2012), which extends learning opportunities beyond the boundaries of the classroom.

Regarding Hypothesis H2, a substantial improvement in visuospatial memory was recorded, with correct answers increasing from 59% to 90% and a large effect size (Cohen's d = 1.95). This result can be interpreted through the lens of embodied cognition, which posits that cognitive processes are closely tied to bodily action and sensory-motor engagement (Shapiro & Stolz, 2019; Wilson, 2002). In this study, students manipulated 3D models via AR interfaces, interacting with historical artefacts and spatial timelines through gestures such as dragging, rotating, and zooming. These embodied interactions enabled students to form more robust mental representations, facilitating spatial encoding and retrieval. As supported by Juan et al. (2014) and Han et al. (2021), the multisensory and interactive nature of AR fosters deeper engagement with spatial features, which may account for the observed enhancement in visuospatial memory.

Turning to Hypothesis H3, the semantic memory test showed a notable increase in performance, with correct responses rising from 53% to 68% (Cohen's d = 1.42). This finding reflects the capacity of AR to support not only visual processing but also verbal encoding and categorisation. The interactive digital stimuli provided students with multimodal representations that facilitated the association and integration of semantic content. This is consistent with the constructivist approach, which highlights how meaningful learning arises from active involvement and contextualisation (Brown et al., 1989), and with theories of situated learning, in which knowledge is acquired within relevant and realistic environments. Furthermore, the persistent and mobile access to AR materials supported the ubiquitous dimension of learning, allowing students to revisit and reinforce semantic content outside scheduled lessons, thereby promoting memory consolidation (Lim et al., 2020; Squires, 2017).

Taken together, the findings suggest that the ATENA methodology leverages the affordances of AR to support memory-related learning processes in primary school students. The improvements observed across all three hypotheses demonstrate that embodied interaction with digital content, personalised access through mobile devices, and contextualised multisensory engagement can significantly enhance both comprehension and memorisation. These outcomes resonate with broader educational goals aimed at fostering autonomy, motivation, and deeper learning in digitally native students, as advocated by recent pedagogical literature (Aljawarneh, 2020; Buchner et al., 2022; Tomassoni, 2021).

Despite the encouraging results, it is important to acknowledge a significant methodological limitation: the absence of a control group and random assignment. The within-subjects design adopted in this study allowed for a preliminary comparison of student performance before and after the AR-based intervention. However, without a randomly assigned control group undergoing traditional instruction alone, it is not possible to attribute observed improvements exclusively to the ATENA methodology or the use of AR. Alternative explanations, such as natural developmental progress, increased familiarity with content structures, or motivational factors unrelated to the intervention, cannot be fully ruled out. As a result, while the findings suggest a promising trend, they should be interpreted with caution. Future studies employing controlled experimental designs, including randomisation and larger, more diverse samples, will be essential to confirm the causal role of AR in enhancing memory processes and to further validate the efficacy of the ATENA approach across educational contexts.

# 5. Conclusion

The findings of this study confirm the effectiveness of the ATENA methodology in enhancing memory-related learning processes, reinforcing the role of AR as an innovative educational tool. The results are consistent with previous research conducted with higher education students, where AR integration significantly improved the retention of didactic stimuli. This study extends the scope of investigation by demonstrating that, in primary school contexts, ATENA can support the development of memory functions, particularly in the domains of visuospatial and semantic memory. From a comparative perspective, while the use of AR in university students primarily facilitated the encoding and retrieval of complex content (Cipollone et al., 2024), in younger learners it appears to have a stronger impact on more foundational memory processes. These outcomes suggest that ATENA may not only reinforce content comprehension but also support the development of memory skills in early education.

It is important to note that the present study did not employ a structured cognitive training protocol, nor did it include neuropsychological measures typically associated with cognitive enhancement interventions. Therefore, any interpretation of ATENA as a cognitive training tool should remain hypothetical at this stage. Future research should investigate this potential by designing dedicated protocols and comparing AR-based activities with established cognitive training programs, particularly in educational domains requiring intensive memory and spatial reasoning.

While the study offers valuable insights, it is not without limitations. First, the sample size was relatively small and limited to a single class, which may affect the generalizability of the results. Future studies should include more diverse student populations from different schools and educational contexts to verify the replicability of the findings. Second, the current research focused on short-term outcomes. Longitudinal studies are needed to determine whether the benefits observed persist over time and contribute to long-term cognitive development. Moreover, although this study targeted primary school students, future investigations could explore the effectiveness of AR-based memory support in older learners, including university students. Finally, examining how AR interacts with individual differences in cognitive profiles and learning styles would allow for more personalised and inclusive educational interventions.

Overall, this study highlights the potential of AR as a transformative component of teaching practices, with particular promise in fostering student engagement, improving content retention, and supporting memory processes in young learners. Further research is encouraged to build on these findings and to develop adaptive, evidence-based AR applications that can enhance learning across different educational stages.

# 6. Author contributions

# 7. References

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