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Special Issue
Extended education as an interconnected ecosystem

Guest Editors
Barbara Bruschi, Laurent Dutoit, Ioannis Lefkos, Manuela Repetto

Italian Journal of Educational Technology

ISTITUTO TECNOLOGIE DIDATTICHE

Dear Readers,

With this first issue of 2026, I am pleased to share several important developments concerning the journal.

The most significant news is that, thanks to the hard work and dedication of our editorial team and reviewers, the Italian Journal of Educational Technology was indexed in Scopus in 2025. This achievement recognizes the scientific quality of our journal and is a source of great pride for all of us. I would like to express my sincere gratitude to everyone who contributed to achieving this important milestone. Elsevier has already retrospectively indexed all issues of the journal published since 2021.

A second piece of news concerns our editorial team. Francesca Pozzi, who has served as Co-Editor of the journal since 2016, has stepped down from this role following her appointment as Director of the Institute for Educational Technology of the National Research Council of Italy (CNR-ITD), a position that entails significant new responsibilities. I warmly congratulate Francesca on this prestigious appointment and wish her every success in her new role. I would also like to thank her for the passion and dedication she has brought to her editorial work, as well as for her significant contributions to shaping the journal's policies in her role as Co-Editor. Without her, much of the good news shared in this letter would not have been possible.

At the same time, I am delighted to welcome Francesca Dagnino to our team of editors. Dr. Dagnino brings extensive editorial experience, both with this journal – having guest-edited several special issues – and with other international journals. I am confident that her expertise and commitment will make a valuable contribution to the Italian Journal of Educational Technology, and I wish her a rewarding and stimulating experience in this new role.

Last but not least, I would like to wish all our readers, authors, reviewers, and editorial board members a productive and successful year ahead.

Donatella Persico
Editor,
Italian Journal of Educational Technology

Gentili Lettrici e Lettori,

Con questo primo numero del 2026, sono lieta di condividere alcuni importanti sviluppi riguardanti la rivista.

La notizia più significativa è che, grazie al lavoro e alla dedizione della nostra redazione e dei revisori, l'Italian Journal of Educational Technology è stata indicizzata in Scopus nel 2025. Questo risultato riconosce la qualità scientifica della nostra rivista ed è motivo di grande orgoglio per tutti noi. Desidero esprimere la mia sincera gratitudine a tutte le persone che hanno contribuito al raggiungimento di questo importante traguardo. Elsevier ha inoltre già indicizzato retrospettivamente tutti i fascicoli della rivista pubblicati dal 2021.

Una seconda novità riguarda il nostro team editoriale. Francesca Pozzi, che ha ricoperto il ruolo di Co-Editor della rivista dal 2016, ha lasciato questo incarico a seguito della sua nomina a Direttrice dell'Istituto per le Tecnologie Didattiche del Consiglio Nazionale delle Ricerche (CNR-ITD), un ruolo che comporta importanti nuove responsabilità. Rivolgiamo a Francesca le nostre più vive congratulazioni per questo prestigioso incarico e i migliori auguri di successo nel suo nuovo ruolo. Desidero inoltre ringraziarla per la passione e la dedizione che ha profuso nel suo lavoro editoriale, così come per il suo importante contributo alla definizione delle politiche della rivista nel ruolo di Co-Editor. Senza di lei, gran parte delle buone notizie contenute in questa lettera non ci sarebbero.

Allo stesso tempo, sono lieta di dare il benvenuto a Francesca Dagnino nel nostro team editoriale. La Dott.ssa Dagnino porta con sé una vasta esperienza editoriale, sia con questa rivista – avendo curato come guest editor diversi numeri speciali – sia con altre riviste internazionali. Sono certa che la sua competenza e il suo impegno costituiranno un prezioso contributo all'Italian Journal of Educational Technology, e le auguro un'esperienza ricca e stimolante in questo nuovo ruolo.

Infine, desidero rivolgere a tutti i nostri lettori, autori, revisori e membri del comitato editoriale i migliori auguri per un anno produttivo e ricco di successi.

Donatella Persico
Direttrice scientifica,
Italian Journal of Educational Technology

Italian Journal of Educational Technology

ISTITUTO TECNOLOGIE DIDATTICHE

Dear Readers,

It is with a touch of melancholy that I step down from this role, as I have been connected to this journal for a very long time. While taking my first steps at the Institute and entering the Educational Technology research field, I carried out my first copy-editing tasks for the journal's papers, followed by my first peer reviews. I then joined the Editorial Board and, over the years, gained my first experiences as a guest editor. In 2016, I took on the role of Co-Editor, a position I have held for the past ten years.

It has been an intense period, marked by challenges and significant changes for the journal. I can proudly say that, during this time, the journal has grown considerably in many respects, culminating in its recent indexing in Scopus – an objective we had pursued for a long time and have finally achieved.

None of this would have been possible without the tireless leadership of Donatella Persico, the great commitment of the editorial staff and all ITD colleagues who work on the journal every day, and the valuable contribution of the International Editorial Advisory Board and our reviewers. Together, they form an outstanding team dedicated to the journal and committed to ensuring a high-quality scientific publication in the field of Educational Technology.

I am pleased to pass the baton to Francesca Dagnino, who I am certain will carry out this role with the high level of professionalism that has always distinguished her. I extend to her my very best wishes for success in this new responsibility.

While I am leaving this role, I am not leaving the journal behind. I will continue to follow and support it in my capacity as Director of the Institute, helping to ensure that it remains the vibrant platform for international dialogue that it is today and continues to contribute to the advancement of research in Educational Technology.

My warmest regards to you all,
Francesca Pozzi

Care lettrici e cari lettori,

è con un pizzico di malinconia che lascio questo ruolo, perché sono legata a questa rivista da molto tempo: mentre muovevo i miei primi passi in Istituto e mi affacciavo al mondo della ricerca sulle Tecnologie Didattiche, facevo i miei primi copy-editing degli articoli della rivista, poi le prime revisioni, fino ad entrare nell'Editorial Board e – con gli anni – ho fatto le prime esperienze da guest editor. Poi, nel 2016 è arrivato il ruolo di co-editor, che ho ricoperto per 10 anni. Un periodo intenso, di sfide e di grandi cambiamenti per la rivista, che – posso dire con orgoglio – è cresciuta notevolmente in questo periodo sotto tanti aspetti, fino ad arrivare alla recente indicizzazione su Scopus, un obiettivo perseguito da tempo e finalmente centrato.

Tutto questo non sarebbe stato possibile senza l'instancabile regia di Donatella Persico, senza il grande impegno della redazione e di tutti i colleghi ITD che si impegnano quotidianamente sulla rivista e senza il contributo dell'International Editorial Advisory Board e dei revisori. Una grande squadra,

al servizio della rivista, che garantisce una pubblicazione scientifica di qualità sui temi delle Tecnologie Didattiche.

Sono contenta di cedere le redini a Francesca Dagnino, che sono certa si impegnerà con l'alto livello di professionalità che la contraddistingue. A lei vanno i miei migliori auguri di buon lavoro.

Lascio questo ruolo, ma non abbandono la rivista: continuerò a seguirla in qualità di Direttrice dell'Istituto e a sostenerla, affinché continui ad essere la vivace piattaforma di confronto internazionale che è oggi, contribuendo all'avanzamento della ricerca nelle Tecnologie Didattiche.

Un caro saluto a tutte e a tutti,
Francesca Pozzi

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Editorial. Extended education as an interconnected ecosystem

Editoriale. Educazione estesa come un sistema interconnesso

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Extended Education is increasingly evolving into a structured and interconnected ecosystem (Arias et al., 2025) in which technological innovation, pedagogical intentionality, and social responsibility converge. If the previous issue framed Extended Education within a technology-augmented world, this issue interrogates how such an expanded educational landscape can become inclusive, sustainable, and cognitively transformative.

The contributions collected in this issue highlight a decisive shift: from technological possibility to pedagogical responsibility. Digital tools – Artificial Intelligence (AI), Augmented Reality (AR), Virtual Reality (VR), and audio-based media such as podcasts – are not presented as ends in themselves, but as mediating infrastructures capable of reshaping access, participation, and professional practice. In this sense, Extended Education emerges not simply as a spatial or temporal extension of learning, but as a qualitative transformation of educational experience.

A first key dimension concerns geographical and cultural extension. The systematic review by Garib et al. on Project-Based Language Learning (PBLL) in the Middle East and North Africa (MENA) region broadens the global perspective on Extended Education. By mapping over four decades of empirical research, the study reveals how PBLL enhances engagement, critical thinking, and language acquisition across diverse educational contexts, despite infrastructural and curricular constraints. Particularly significant is the role attributed to teacher professional development and technological availability: innovation does not spread automatically but requires systemic investment in educator competence and institutional support. Extended Education, therefore, is not simply about adopting methods; it is about enabling conditions for their meaningful implementation.

A second dimension relates to inclusion and accessibility as structural principles. The contribution by Del Bianco et al. situates Extended Education within the framework of cultural rights and social participation. Through the integration of AR, VR, and AI in museum environments, their project demonstrates how digital technologies can enhance accessibility for individuals with intellectual disabilities and autism. Museums become inclusive learning spaces, where immersive and adaptive tools facilitate

participation and well-being. Here, Extended Education expands beyond formal schooling and affirms itself as a lifelong and life-wide process, deeply connected to citizenship, equity, and human dignity.

In parallel, Pecoraro's study on educational podcasts in teacher training underscores the strategic importance of preparing future support teachers to use digital tools critically and effectively. The structured evaluation of podcast creation applications and their pedagogical integration reveal that technological innovation must be accompanied by methodological rigor. Podcasts, often perceived as simple media tools, are reframed as instruments for fostering inclusion and personalized learning pathways. Extended Education thus depends not only on advanced technologies but also on the professional agency of teachers capable of selecting, evaluating, and adapting tools to diverse learner needs.

The cognitive implications of technology integration are further explored by Lembo et al., whose six-month intervention in primary education examines the impact of Augmented Reality on memory processes. Their findings – showing improvements in content acquisition, visuospatial memory, and semantic memory – suggest that AR can meaningfully support cognitive encoding and retrieval even at early developmental stages. Importantly, the intervention was not designed as formal cognitive training, yet it produced measurable effects on memory-related functions. This contribution invites us to consider Extended Education not only as expanded access but also as enhanced cognitive architecture: technologies can scaffold mental processes when embedded in coherent pedagogical design.

Finally, Paludo's study addresses one of the most debated terrains of contemporary education: generative AI in programming and computer science learning. Rather than framing AI as a threat to academic integrity, the research proposes a metacognitive paradigm in which AI-generated code becomes a catalyst for reflection, creativity, and higher-order thinking. The reported improvements in AI literacy and metacognitive awareness among students indicate that the question is no longer whether AI should be present in educational contexts, but how it can be orchestrated to cultivate critical competencies. Extended Education, in this perspective, requires a shift from tool control to cognitive regulation – where learners develop the ability to supervise, interpret, and critically evaluate AI outputs.

Across these diverse contexts – language education in MENA, inclusive museum environments, teacher training, primary education, and programming – common threads emerge.

First, teacher professionalism is central. Professional development, methodological competence, and evaluative capacity are consistently identified as preconditions for effective innovation.

Second, accessibility is not peripheral but foundational. Whether addressing disability, geographical disparities, or technological gaps, Extended Education must be anchored in equitable design.

Third, cognitive and metacognitive development represents a crucial horizon. Technologies become transformative when they strengthen critical thinking, memory processes, creativity, and reflective judgment.

This issue thus reframes Extended Education as an interconnected and inclusive ecosystem – one that integrates technologies within pedagogical intentionality, institutional support, and ethical awareness. The augmented world is no longer an emerging scenario; it is an operational reality. The challenge ahead lies in ensuring that this reality remains human-centred, cognitively meaningful, and socially equitable.

1. References

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Project-based language learning in the Middle East and North Africa: An AI-assisted systematic review

Apprendimento linguistico basato su progetti in Medio Oriente e Nord Africa: una revisione sistematica assistita dall'intelligenza artificiale

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ABSTRACT Project-based language learning (PBLL) is unarguably popular worldwide. However, how commonly is this approach implemented in the Middle East and North Africa (MENA)? To find out, a systematic review of research on MENA's PBLL practices was conducted to shed light on the region. Using a qualitative analysis approach with the assistance of generative artificial Intelligence (GenAI), this article reviews PBLL empirical research from 1980 to 2024 in MENA. Four themes emerged: PBLL implementation and effectiveness, PBLL form and function, PBLL technological integration, and challenges implementing PBLL. PBLL, which slowly began to increase in popularity in the early 2000s in MENA, was found to enhance language teaching, learning, student engagement, and critical thinking across the MENA countries, despite varying degrees of challenges. The findings stressed the role of teacher professional development and the availability of technological resources for successful PBLL implementation. The study concludes with recommendations for PBLL in MENA.

KEYWORDS Project-Based Language Learning; Under-Resourced and Better-Resourced Contexts; Middle East and North Africa; Innovative Qualitative Data Analysis with AI; Systematic Review.

SOMMARIO L'apprendimento linguistico basato su progetti (Project-Based Language Learning, PBLL) è indubbiamente molto diffuso a livello globale. Tuttavia, quanto è effettivamente comune questo approccio nel Medio Oriente e Nord Africa (MENA)? Per rispondere a questa domanda è stata condotta una revisione sistematica della ricerca sulle pratiche PBLL nella regione, con l'obiettivo di fare chiarezza sulla situazione in quel contesto. Utilizzando un approccio di analisi qualitativa, supportato dall'intelligenza artificiale generativa (GenAI), questo articolo esamina la ricerca empirica sul PBLL nel MENA dal 1980 al 2024. Sono emersi quattro temi principali: l'implementazione e l'efficacia del PBLL, la forma e la funzione del PBLL, l'integrazione tecnologica nel PBLL e le sfide legate alla sua attuazione. Il PBLL, che ha iniziato a diffondersi gradualmente nei primi anni 2000 nella regione MENA, ha migliorato l'insegnamento e l'apprendimento linguistico, il coinvolgimento degli studenti e il pensiero critico nei vari Paesi della regione, nonostante differenze nel livello delle difficoltà riscontrate. I risultati hanno evidenziato il ruolo della formazione professionale degli insegnanti e della disponibilità di risorse tecnologiche per una implementazione efficace del PBLL. Lo studio si conclude con una serie di raccomandazioni per l'adozione del PBLL nella regione MENA.

PAROLE CHIAVE Apprendimento delle Lingue Basato su Progetti; Contesti Didattici Poveri di Risorse; Medio Oriente e Nord Africa; Analisi Qualitativa dei Dati con Intelligenza Artificiale; Revisione Sistematica della Letteratura.

1. Introduction

In language education, project-based language learning (PBLL) has proven to be highly engaging (Beckett, 1999; Thomas, 2000; Nami, 2021) due to real-life relevance of project work to students (Beckett et al., 2020b). This approach fosters linguistic skills (form and function) and cultivates critical thinking, collaboration, and digital literacy (Beckett, 2023). Beckett et al. (2020b) stress the importance of language form and function in PBLL, emphasizing that "*there has been little research, especially experimental research, addressing how PBL promotes the development of language form and function, particularly in technology-mediated PBLL contexts*" (p. 8). Over the past several decades, the implementation of PBLL has gained enormous popularity, resulting in its application in many different contexts globally, including the Middle East and North Africa (MENA) region.

The MENA region, which is characterized by its linguistic diversity and an unfortunate lack of educational and professional resources (Akkari, 2004; Hos & Cinarbas, 2017), provides a rich context for understanding the application of PBLL with or without the assistance of technology. However, the effectiveness and implementation of PBLL in MENA, specifically in under-resourced contexts, have not been fully explored (Garib, 2022; 2024; Thomas & Yamazaki, 2021). To address this need, this article overviews PBLL's global practices, sheds light on English language teaching in MENA and examines published research on PBLL in MENA to understand how, over time, this pedagogical approach has been applied in various settings. Because the state-of-the-art generative artificial intelligence (GenAI) offers opportunities for novel methodologies in conducting qualitative systematic review studies (Hamilton et al., 2023; Hosseini et al., 2023; Morgan, 2023), this study takes a step forward with its methodology by using GenAI as an assistant for the systematic review. The study contributes to the broader field of educational technology, teaching, and learning by exploring the challenges and opportunities of implementing PBLL with or without educational technology in MENA, which can guide teachers, policymakers, and researchers in similar contexts globally.

1.1. Overviewing PBLL's global practices

PBLL's global practices reveal a diverse implementation spectrum. For instance, PBLL has a decades-long history that can be traced back to several regions. In Asia, PBLL has been adapted to enhance students' language engagement (Kelsen, 2018) and deepen their linguistic understanding through the integration of relevant cultural elements (Wang, 2020). In Europe, PBLL gained attention for its cross-cultural communication and collaboration, preparing students for a globalized workforce (Lewin & McNicol, 2015; Sato & Horne, 2020). In North America, project work has been well-known for its effectiveness in general and language education (Beckett, 1999; Beckett et al., 2015; Beckett et al., 2020a; Beck & Kurt, 2022). These contextual variations in practice show the practicality of PBLL in different well-resourced educational contexts. However, a shift towards the exploration of PBLL in under-resourced contexts is needed (Garib, 2022; 2024; Thomas & Yamazaki, 2021).

The implementation of PBLL in many under-resourced contexts, particularly within MENA, has not been explored adequately (Nasr & Wilby, 2017; Romanowski & Karkouti, 2021; Rahme & Altamimi, 2022). The discussion of PBLL in MENA can uncover unique practices and contextual challenges. This region has endured continuous challenges, such as economic crises, political instabilities, natural disasters, wars, and politically motivated technological inaccessibility (Jahanshahi et al., 2020). Such factors can negatively impact the implementation of educational innovations like PBLL. High-

lighting the need for further exploration of PBLL practices in MENA addresses future solutions and challenges. Before delving into PBLL practices in MENA, reviewing language teaching practices in this region is necessary to understand how PBLL fits in such contexts. The following section explores the region's English language teaching (ELT) norms and challenges.

1.2. ELT challenges and opportunities in the MENA region

The MENA region "*has been thinking high of the English language, since research-wise, English is perceived as the only way out...a country to receive international recognition and [for its universities to receive a] good ranking*" (Hidri 2019, p. 38). The status of this region can be viewed in two ways: better-resourced and under-resourced countries. According to the United Nations' Country Classification Report (2024), the oil-producing countries such as the UAE, Qatar, Bahrain, Kuwait, Oman, and Saudi Arabia fall into the better-resourced category, which benefit from well-funded education systems, access to modern educational technologies, and an emphasis on English language learning as a component for global engagement. In contrast, countries like Yemen, Libya, Syria, Iraq, Lebanon, Tunisia, and parts of rural Egypt and Morocco are considered under-resourced (UN Report, 2024), facing challenges due to weak infrastructure, limited educational materials, and scarce teacher training within local contexts.

These contextual disparities can affect the implementation and outcomes of ELT across the region, with under-resourced contexts struggling to keep pace with their more affluent counterparts (Kuchah, 2018). For example, in MENA's under-resourced contexts, curriculum design often fails to meet students' needs due to outdated curricula and policymakers' resistance to adopt programs suitable for their local contexts (Abubaker et al., 2025; Farag & Yacoub, 2023; Hayes, 2012). Hayes adds that such practices are due to policymakers' overemphasis on international educational systems that were developed for other contexts. In light of this, Farag and Yacoub (2023) explained that such educational "*policy innovations unfortunately do not emanate from baseline research. They are most often borrowed from other contexts where they have worked well*" (p. 245). Another challenging factor is the limitation of teacher autonomy, with educators frequently operating under rigid curricular constraints that leave little room for innovation or adaptation to local contexts (Hos & Cinarbas, 2017). Additionally, professional development opportunities for teachers are scarce (Garib, 2022), preventing teachers from keeping up with the latest pedagogical strategies and research in language teaching. Moreover, issues with technology integration are common, as many schools lack the necessary infrastructure or resources to implement educational technology effectively (Daoud, 2019; Al-Jaro, 2023).

Such challenges can disrupt ELT, resulting in a failure to achieve language teaching and learning goals. However, despite these challenges, there is a growing recognition of the need for more interactive and engaging teaching approaches in the MENA region's ELT, more specifically the adoption of interactive approaches such as PBLL (Abubaker et al., 2025; Garib, 2022; Garib & Schmidt-Crawford, 2025). To explore this need, a systematic review of PBLL practices can assist in understanding PBLL's practices in MENA, which is the goal of this study.

1.3. Focus of the study

Beckett and Slater (2020) discussed research gaps in PBLL literature, including expanding the contextual exploration of PBLL research beyond North America, PBLL's development of English language form and function, technology integration and assessment, and teacher training for technology integra-

tion. In response to Beckett et al.'s (2020) call for a regional understanding of teachers' PBLL practices, this study conducts a systematic review of research on MENA's PBLL practices to explore this region's distribution of PBLL research publications and project implementation from 1980 until 2024. The guiding research questions for this exploration are:

- What varying distribution (if any) are there in the implementation and publication of PBLL research in the MENA region from 1980 to 2024?
- What do MENA PBLL research studies report on the implementation of PBLL and its impact on the learning of language form and function?
- What challenges and technology tools (if any) are commonly mentioned in the PBLL MENA studies, and how do these factors differ between well-resourced and under-resourced contexts?

2. Research methodology

This systematic review employed a structured approach to gather, select, and synthesize empirical research on project-based language learning (PBLL) in the Middle East and North Africa (MENA) region, covering the period from 1980 to 2024, because PBLL work began to appear in the 1980's (Beckett, 1999; Beckett et al., 2025). This study is part of an ongoing larger study (Beck & Kurt, 2022; Beckett et al., 2025), which examines PBL/L research worldwide. The identification of MENA countries in this study follows the UN's Country Classification (2024).

Drawing on established methodological frameworks (Macaro et al., 2012; Page et al., 2021; Reinders et al., 2023) for systematic reviews, this qualitative study documents the various implementations of PBLL for data collection and data analysis. This review takes an innovative initiative by using generative artificial intelligence (GenAI) in the analysis, namely AI-assisted analytical techniques, to examine the PBLL literature within MENA, which enhanced the depth and breadth of the study's qualitative analysis.

2.1. Data collection

To ensure rigor in the selection of empirical research articles, the authors adhered to PRISMA's three guiding steps (Chong & Reinders, 2021; Page et al., 2021): identification, screening, and inclusion. Following such a process maintains a systematic procedure for a transparent, replicable, and methodologically sound research selection, which aligns with the standards for systematic reviews (Moher et al., 2009). Figure 1 outlines these three processes in this study. Figure 2 illustrates the steps taken in the PRISMA-guided data collection procedure.

2.2. Data analysis

Once the selection of articles was completed, the researchers, following Macaro et al.'s (2012) framework, independently read and reviewed each article and recorded their summaries in an Excel spreadsheet. The spreadsheet prompted researchers to record details on each research study, including the type of the study, research foci, technology used, theoretical orientation, macro and micro contexts, participants, research methods, data sources, major findings, conclusions/implications, and general comments. Following the thorough manual summarization of the selected empirical research articles, the first author took two steps:

1 Identification

To identify data for collection, the search was conducted across seven electronic databases covering educational and psychological literature (Beckett et al., 2025): Academic Search Complete, ERIC, MLA Full Texts, Linguistics and Language Behavior Abstracts (LLBA), MLA International Bibliography Full Text, Social Sciences Dissertation Abstracts, and PsycINFO. As pointed out in Beckett et al. (2025), these selected databases are recommended for scholarly communities in the U.S and Canada. Search terms included combinations of "technology-assisted learning," "project-based learning," "PBL," "PBLL," "creativity and innovation," "collaboration or cooperative work," "digital literacy and disciplinary literacy," "autonomy or self-management," "independent decision making or independence," "engagement or motivation," "self or social awareness," "ownership and agency," "self-awareness or social awareness," and "Middle East & North Africa/MENA."

2 Screening

The retrieved studies were screened for the selection process following the Cochrane systematic review criteria (Higgins et al., 2019), which focuses on the population (MENA region), phenomena of interest (PBLL/TAPBLL), and context (educational settings). The gathered articles were screened based on title, abstract, written in English language only, and full text to determine relevance in a Mother Folder, which was the main folder of all collected articles in the host university Box folder, as recommended by Booth et al. (2012).

3 Inclusion

All PBLL journal articles about the MENA region were identified and included in a separate sub-folder. PBL studies were excluded due to limited/no focus on language learning. Out of 620 articles, the first author identified a total of 62 PBLL empirical research articles that focused on the implementation of PBLL in different micro contexts, including middle school, high school, and post-secondary in the macro context of MENA. Of these 62 studies, 61 were included for analysis in the current study (see Figure 2). These gathered articles are published in English only.

Figure 1. PRISMA's guiding steps.

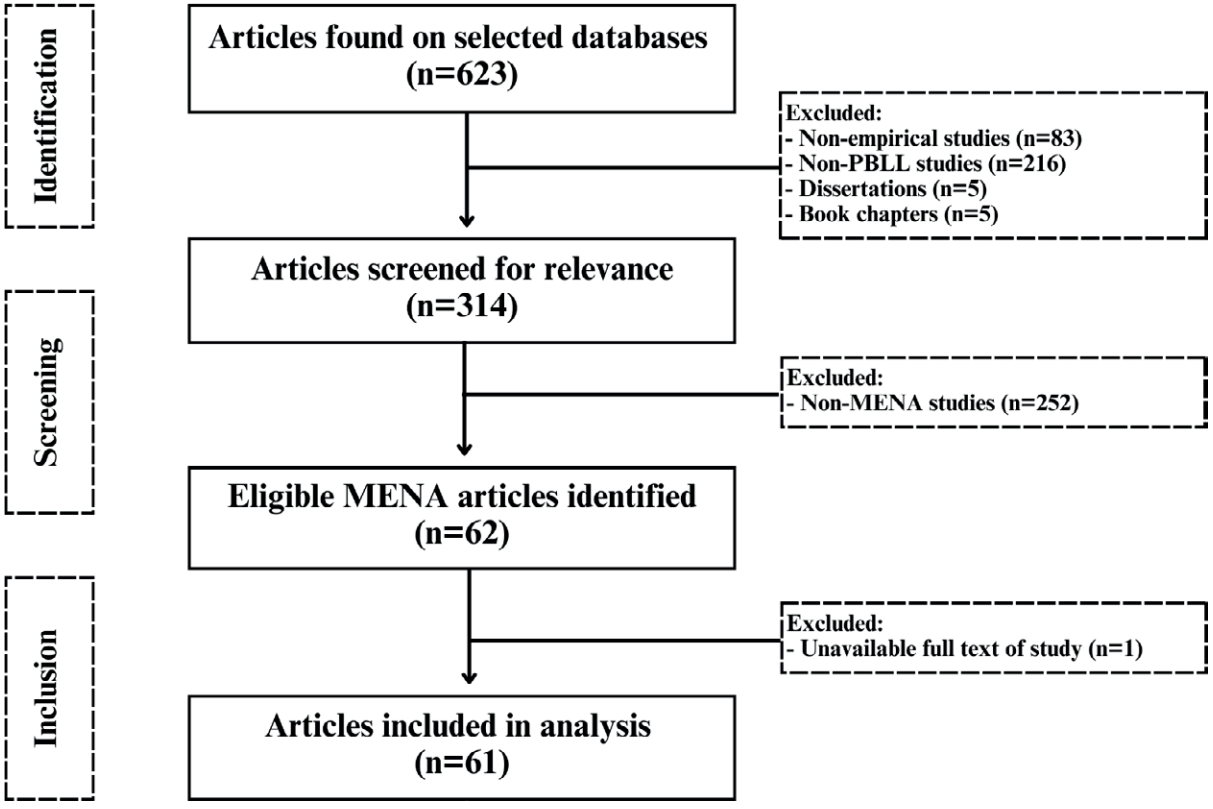

Figure 2. PRISMA-guided data collection procedure.

(1) used OpenAI's ChatGPT (version 4o, 2024) to conduct a human-led thematic analysis of the human-written summaries
(2) employed NVivo to analyze and validate the same dataset thematically.

To adhere to research ethics, the text of the original research studies was not inputted into ChatGPT. Instead, the first author provided only the human-written summaries for ChatGPT to perform the data analysis in the temporary chat mode. The following provides detailed overview of both steps.

2.2.1. Step 1: Using OpenAI's ChatGPT for thematic analysis

Why was ChatGPT used as an analysis tool? The appearance of GenAI in all aspects of academic practices, including education and research, necessitates the adoption of new perspectives (Chapelle, 2024), which, in turn, can offer enhancements in human productivity (Khalifa & Albadawy, 2024) and efficiency in data analysis (Hosseini et al., 2023; Garib & Coffelt, 2024; Garib et al., 2024). For instance, Hamilton et al. (2023) stress that ChatGPT can "*supplement complex human-centered tasks such as qualitative research analysis*" (p. 13) by identifying emerging themes in data. Furthermore, Morgan (2023) highlights that GenAI tools "*have the power to disrupt the coding of data segments as a dominant paradigm for qualitative data analysis*" (p. 1), suggesting the use of GenAI can reduce the time and workload of traditional methods. However, such uses of GenAI should be ethically sound, as Hosseini et al. (2023) advocate for the responsible use of GenAI in research analysis to ensure research "*transparency, accountability, fair allocation of credit, and integrity*" (p. 462). To maintain such research integrity, human intervention is necessary (Castillo-González, 2023), as is the case in the current study.

Building on the recommendations for using GenAI for data, the current study takes an innovative initiative by employing ChatGPT in qualitative analysis. Guided by Braun and Clarke's (2019) thematic analysis, the first author prompted ChatGPT to analyze the data using several steps: initial coding, categorization, and theme development, which were followed by extensive human revisions. Due to ChatGPT's potential limitations in conducting qualitative analysis (Morgan, 2023) and to avoid any possible GenAI hallucinations (Mahmoudi et al., 2024), the human revision step was integrated as a continuous process, occurring after each step of the analysis, to ensure the accuracy of the data throughout, rather than being conducted only at the end. The human revisions were guided by Braun and Clarke's overarching thematic analysis principles, which emphasize semantic coherence, relevance to the research questions, and representativeness across the dataset. More specifically, the themes were evaluated based on their internal consistency and alignment with the summaries' actual content. In cases where discrepancies arose, the first author prioritized the data-relevant meanings over abstract patterns. It is important to note that these judgments were not purely intuitive. That is, the first author followed the analytical logic of coding saturation, relevance of the categories to the codes, and the interpretive coherence of the dataset.

The first author prompted ChatGPT to generate initial codes by identifying recurring words and phrases across the human-written summaries of the articles. This was done using a prompting approach guided by Garib et al.'s (2024) framework of basic, detailed, and trained prompting techniques. In the initial coding phase, basic prompts were used, for example: "Identify recurring keywords or concepts in the summaries," which allowed ChatGPT to surface lexical patterns and frequently mentioned terms. In the categorization phase, the process moved to detailed prompting, where ChatGPT was asked to group related codes into conceptual categories. An example prompt included: "*Based on the summaries and the codes you just generated, cluster these codes into broader categories that reflect*

the PBLL-related practices within the summaries." During this phase, discrepancies between the human and GenAI were observed then resolved through repeated review. The next step included developing these categories into emerging themes that represented the research findings within summaries. In the theme development stage, the first author used trained prompting to guide ChatGPT in generating thematic interpretations. For instance, a prompt example can be exemplified in: "*Based on the categories you generated, identify overarching themes that capture patterns in PBLL implementation, instructional focus, and contextual barriers across the MENA studies within the summaries*." These steps required constant back-and-forth prompting with ChatGPT as well as thorough revision and comparison with the original human-written summaries.

Although ChatGPT's theme identification was a helpful guide, its output cannot (and should not) be used as a final analysis version due to its limitations and tendencies to hallucinate. For example, ChatGPT's coding was precise and insightful, but a discrepancy of approximately 19% was observed when compared with the first author. While the AI-generated codes initially appeared clear and relevant, a closer examination revealed inconsistencies that warranted further analysis. These discrepancies were of two types:

(1) hallucinations (made up or nonexistent details) and
(2) micro-coding (too precise that it lost track of actual representation of data).

ChatGPT initially generated a recurring category of "learning outcomes". However, the human reviewer identified that "student engagement" was a relevant category because the focus was on the action of the learning, not the overall result. A key takeaway from these discrepancies is that, in certain situations, GenAI can be so precise that it paradoxically leads it to overlooking broader patterns, or at times, simply makes up information. Catching hallucinations was more manageable than micro-coding. Micro-coding can create confusion and distraction from the main focus. Therefore, the first author, who was also critical of all codes and themes that ChatGPT generated, repeatedly revised all ChatGPT's output to assure accurate alignment with the data. For precise coding and analysis, human oversight of GenAI output is needed at all times.

2.2.2. Step 2: Using NVivo for validation and cross-comparison

To further address the potential limitations of relying on GenAI as an only tool for the data analysis, and also to ensure the credibility and rigor of the qualitative analysis, the first author used the NVivo software to cross-validate the themes generated by ChatGPT. NVivo is a purpose-built tool for qualitative data analysis, which provides structured coding, visualization tools, and frequency analysis (Garib, 2024). The human-coded summaries were imported into NVivo and analyzed manually by the first author (see Figure 4). Through NVivo's systematic coding functions, the themes reflected their frequency in the data (see Figure 3).

This approach to data analysis, along with the human expertise and GenAI precision, triangulated the data analysis and added richness and multifaceted understanding of the human-AI collaboration. Using ChatGPT certainly enriched the analysis and provided several benefits that might have been missed by the human reviewer alone. One observation was that ChatGPT's ability to process large volumes of data quickly helped in identifying categories, patterns, and themes that might not have been apparent to the human reviewer using NVivo. For example, while the human reviewer noted "student engagement" as an important category, ChatGPT was able to identify nuanced codes within this category, such as "peer interaction" and "self-motivation," which were initially overlooked. Additionally, ChatGPT's

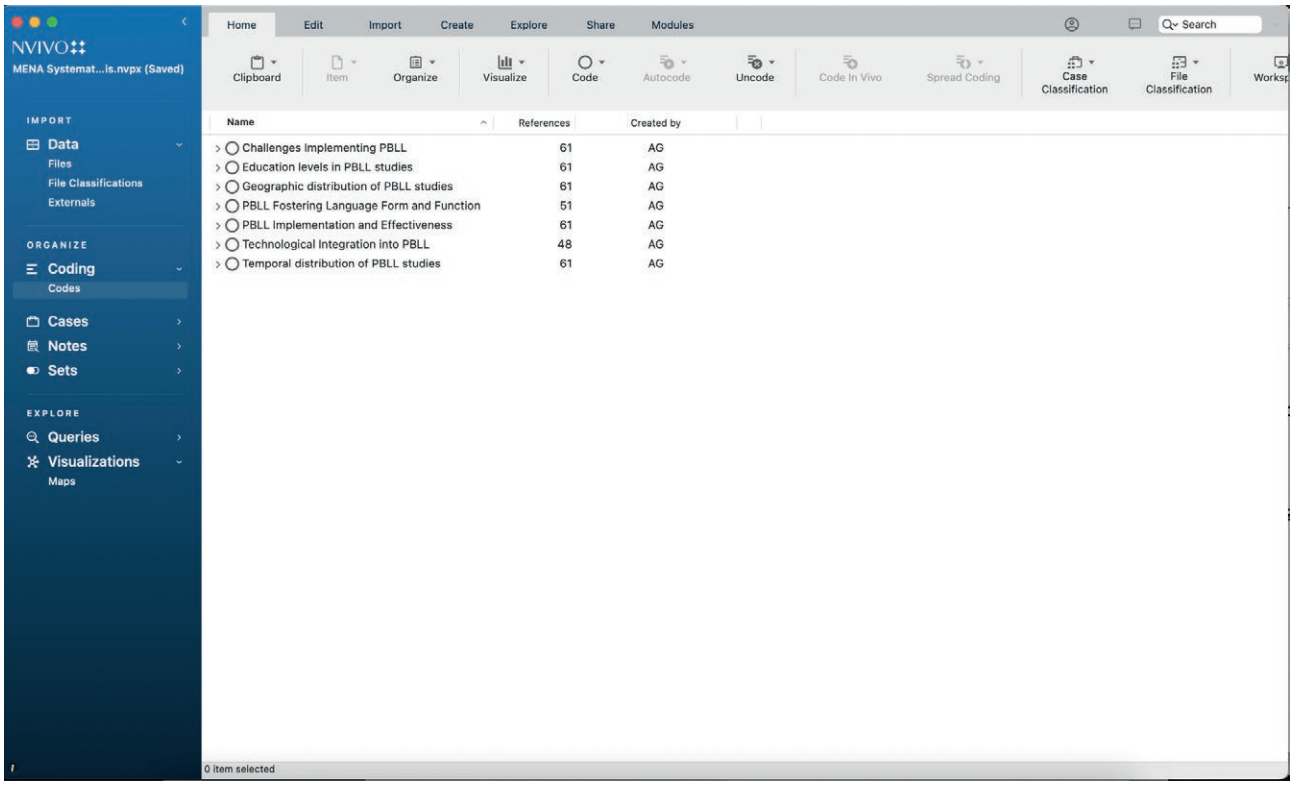

Figure 3. Frequency of emerging themes.

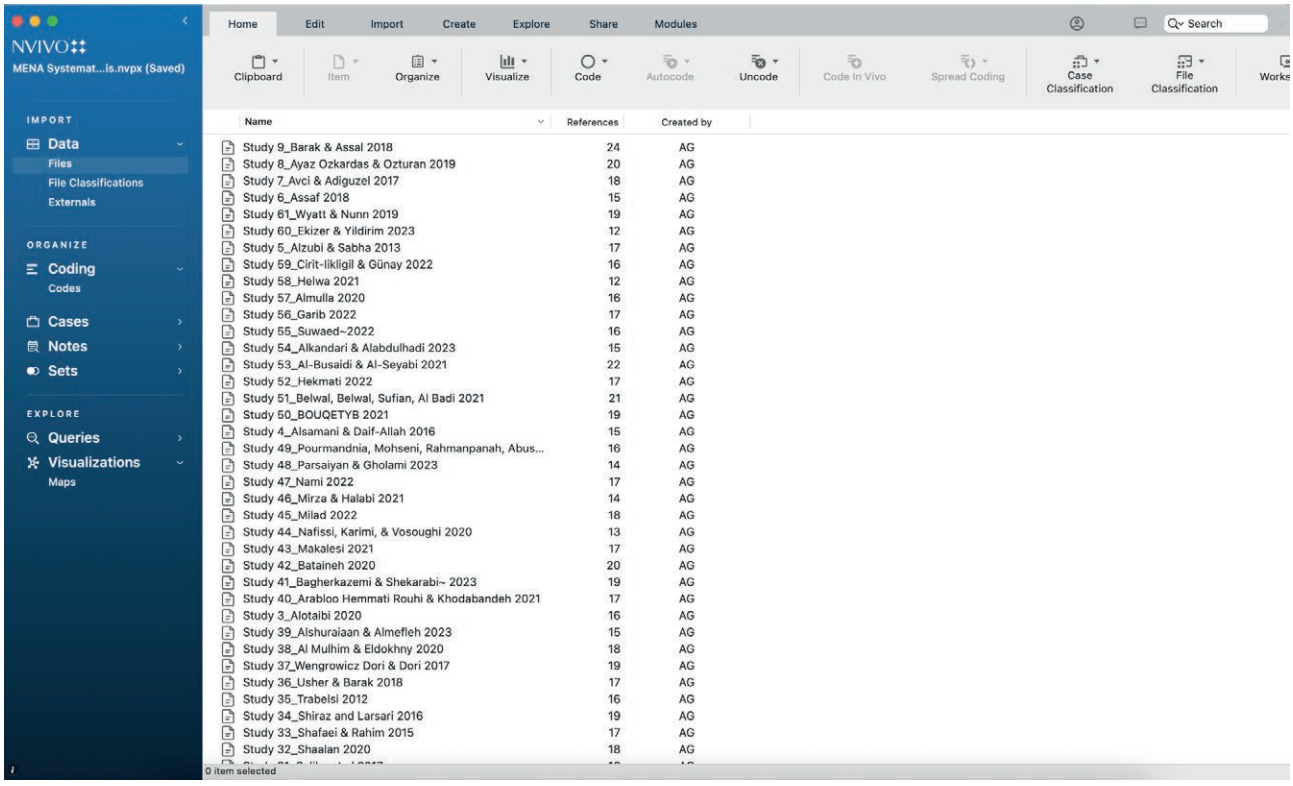

Figure 4. References to codes in the human-written study summaries.

suggestions prompted the human reviewer to reconsider and refine their categories, which led to a more thorough analysis. To further examine the alignment between the human-coded and ChatGPT-coded thematic analysis, the first author compared and calculated the simple percentage agreement for the coding outcomes for the four main emergent themes: PBLL Implementation and Effectiveness, Fostering Language Form and Function, Technological Integration, and Challenges. It is important to note that the other three emerging themes: Education Levels, Geographic Distribution, and Temporal Distribution, were not included in the percentage agreement analysis because they are descriptive or categorical themes rather than interpretive. That is, these themes were automatically identified in every study, since each article reported where and when the study took place and what education level was involved.

Based on the NVivo analysis of the 61 studies, the highest alignment between ChatGPT and the human coder was observed in PBLL Implementation and Effectiveness (coded in 61 studies), followed by Technological Integration (coded in 48 studies), and Fostering Language Form and Function (coded in 51 studies). The lowest agreement occurred under the theme of Challenges Implementing PBLL (coded in 61 studies), where interestingly ChatGPT struggled to distinguish between the nuanced contextual constraints, despite the fact that all the 61 studies reported some form of barriers (See Figure 3). With that being stated, the broad agreement rate across the four themes was 81%, with the most consistent coding appearing in categories that involved explicit language. For example, surface-level and clearly stated technologies or stated instructional outcomes were commonly agreed upon. In contrast, the other themes, Challenges Implementing PBLL and Language Form/Function, relied on more abstract interpretations, especially where ChatGPT tended to misinterpret contextual or pedagogical nuance. These results are consistent with current literature (Garib & Coffelt, 2024; Nyaaba et al., 2025; Yan et al., 2024), which indicates that GenAI tools are suited for surface-level thematic identification but are less reliable in distinguishing or identifying complex and context-related meanings. These observations reinforce the importance of human oversight in qualitative analysis as well as highlight the complementary potential of GenAI to augment, but not replace, human judgment.

3. Findings

This section introduces the findings of our systematic review of PBLL research in the Middle East and North Africa region from 1980-2024. This study sought to determine the distribution of PBLL publications in the MENA region, what research studies in the region report on the implementation of PBLL and its impact on the learning of language form and function, and the challenges and technology tools that are commonly addressed within well-resourced and under-resourced MENA contexts. These resulting findings provide a better sense of PBLL publications and research in the region and help determine future directions. The results are presented in response to the three research questions in this study.

3.1. RQ#1: Distribution in the implementation and publication of PBLL research in MENA from 1980 to 2024

In response to RQ#1, three factors illustrated the varying distributions in the implementation and publication of PBLL research among countries in MENA from 1980 to 2024. These factors include temporal distribution of PBLL studies, geographic distribution of PBLL studies, and education levels or grades investigated in PBLL studies.

3.1.1. RQ#1: Temporal distribution of PBLL studies

The included studies were not conducted evenly between 1980 and 2024. A noticeable increase in PBLL research occurred in the mid-2000s. From 1980 to 2005, there were no known PBLL studies published in the MENA region in English. Starting in 2006, the number of studies began to rise gradually, with one study each year in 2006, 2008, 2010, and 2012, except in 2013, where there was a slight spike with three studies. From 2014 to 2017, the number of studies fluctuated, with a notable increase starting in 2015, where four studies were published. This trend continued with five studies in 2016 and four studies in 2017. In 2018, there were four studies, followed by an increase to six studies in 2019. A sharper rise occurred in 2020 with seven studies, peaking in 2021 with ten PBLL studies published. The number of studies slightly decreased to seven in 2022 and six in 2023. The absence of studies in 2024 might indicate that research for this year has not been published yet, but more studies may appear in the near future. This overall research progress suggests a growing interest and an accelerating pace of research in PBLL practices within the MENA region (see Figure 5).

3.1.2. RQ#1: Geographic distribution of PBLL studies

Figure 6 illustrates the number of PBLL studies included from each country to provide an overview of the research distribution across the Middle East and North Africa (MENA) region. However, our search did not yield any PBLL empirical research articles in other MENA contexts, such as Bahrain, Djibouti, Mauritania, Somalia, Sudan, and Yemen. While it is noticeable that extensive research was conducted in Turkey and Iran, it was surprising that well-resourced MENA countries, such as Kuwait, Oman, Qatar, Saudi Arabia, and UAE, have relatively fewer studies published on PBLL in English. Despite their advanced educational infrastructures, these countries seem to have less documented

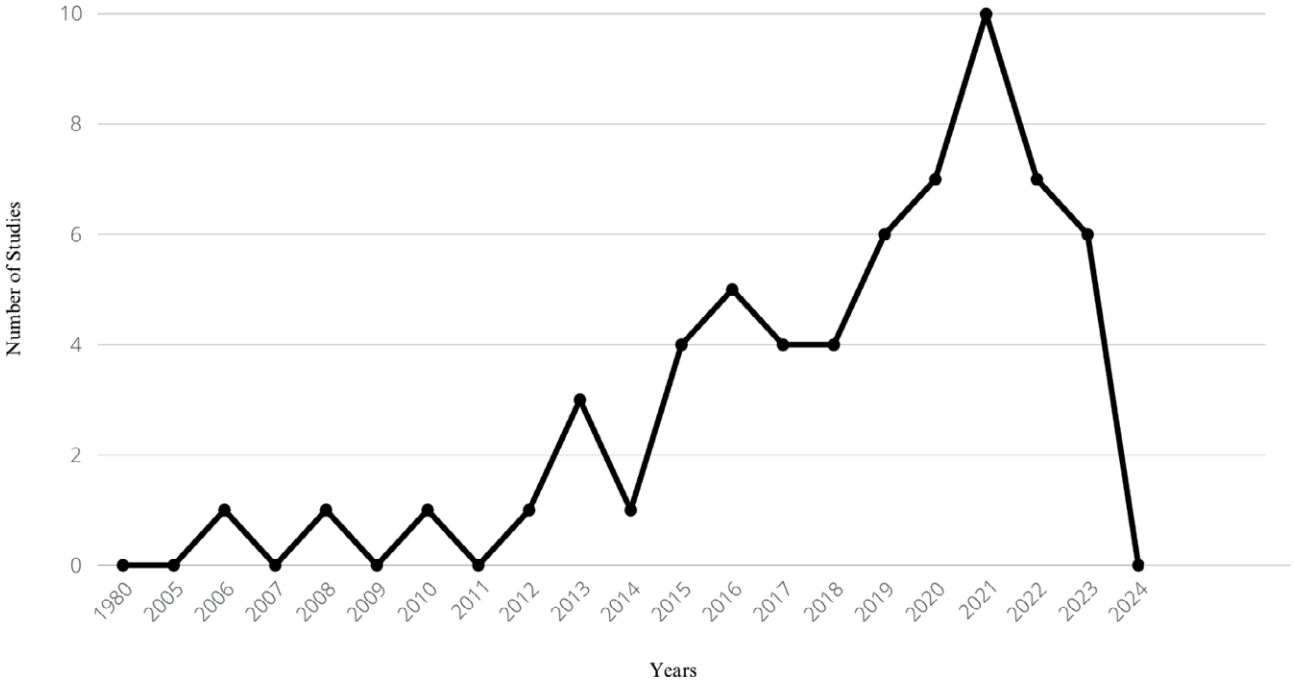

Figure 5. Number of PBLL studies published in MENA between 1980-2024.

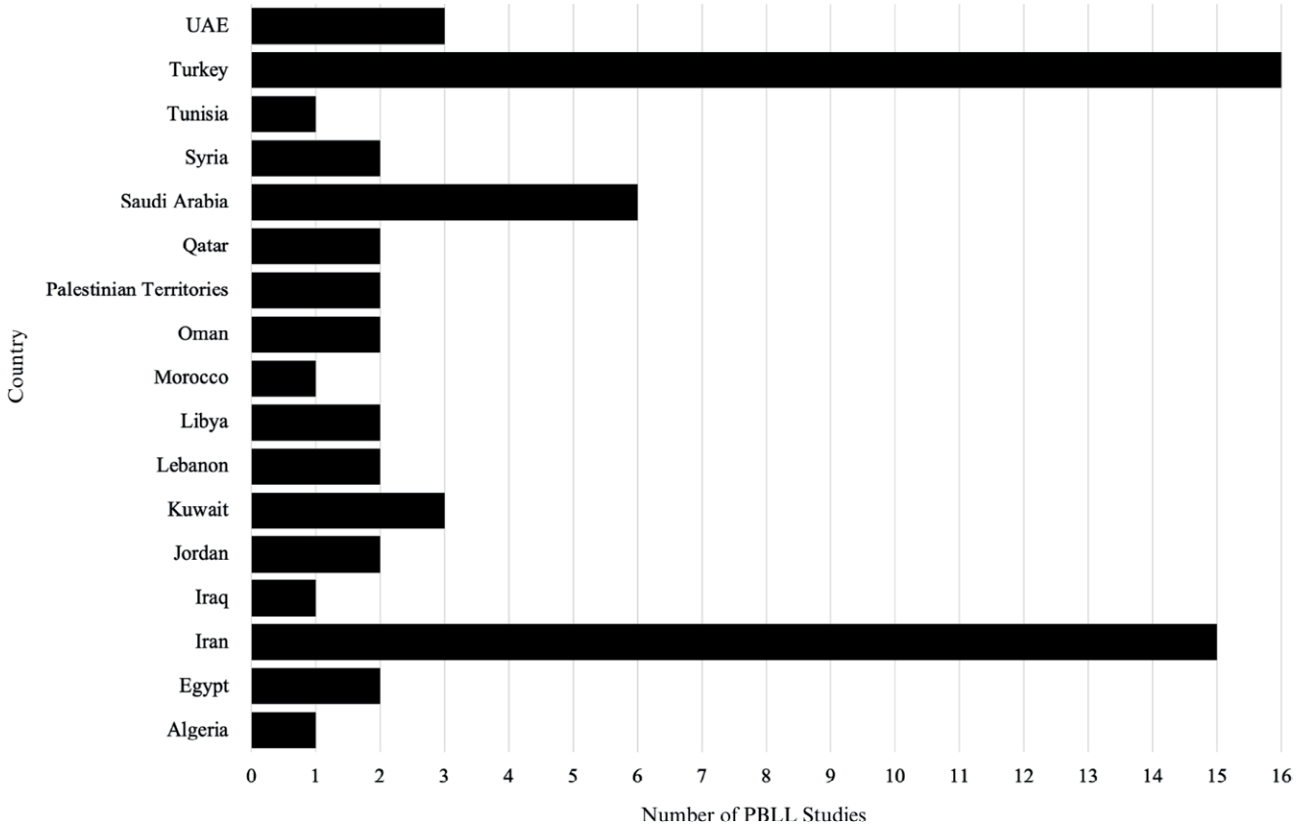

Figure 6. Number of PBLL studies per country.

research on PBLL, which could suggest either a less emphasis on this teaching approach or possibly underreporting in academic publications in English included in the databases we searched. Such limited PBLL visibility highlights a potential area for further investigation into the implementation of PBLL in the well-resourced MENA countries.

For a specific reference to the collected studies, Table 1 complements Figure 6 by listing the studies analyzed. Such data aid in understanding the breadth and focus of PBLL research within the MENA region.

3.1.3. RQ#1: Education levels in PBLL studies

As Figure 7 shows, the studies in Table 1 included four micro contexts: elementary school (n=4), middle school (n=6), high school (n=16), and college-level education (n=43). Some studies included multiple education levels.

The systematic review of PBLL studies across the MENA region identified four major themes: (RQ#2) PBLL implementation and effectiveness, PBLL fostering language form and function, (RQ#3) technological integration into PBLL, and challenges implementing PBLL. These themes provide a detailed overview of the various, yet unique, implementations of PBLL across the different countries in MENA.

Table 1. The analyzed PBLL studies

Country	Analyzed PBLL Studies
Algeria	Boudersa & Hamada, 2015
Egypt	Shaalan, 2020; Helwa, 2021
Iran	Alavinia & Qoitassi, 2013; Maftoon et al., 2013; Moghaddas & Khoshsaligheh, 2019; Mohamadi, 2018; Reisi & Saniei, 2016; Sadeghi et al., 2016; Shafaei & Rahim, 2015; Shiraz & Larsari, 2016; Arabloo et al., 2021; Bagherkazemi & Zahed Shekarabi, 2023; Nafissi et al., 2020; Nami, 2022; Parsaiyan & Gholami, 2023; Pourmandnia et al., 2021; Hekmati, 2022
Iraq	Kavlu, 2017
Jordan	Alzu'bi & Sabha, 2013; Bataineh et al., 2020
Kuwait	Koushki, 2019; Milad, 2022; Alshuraiaan & Almefleh, 2023
Lebanon	Mirza & Halabi, 2021; Garib, 2022
Libya	Garib, 2022; Suwaed, 2022
Morocco	Bouqetyb, 2021
Oman	Al-Busaidi & Al-Seyabi, 2021; Belwal et al., 2021
Palestinian Territories	Bakeer et al., 2023; Migdad et al., 2021
Qatar	Du et al., 2019; Saliba et al., 2017
Saudi Arabia	Alotaibi, 2020; Alsamani & Daif-Allah, 2016; Khodary et al., 2017; Madkour, 2016; AlMulhim & Eldokhny, 2020; Almulla, 2020
Syria	Assaf, 2018; Garib, 2022
Tunisia	Trabelsi (2013)
Turkey	Avci & Adiguzel, 2017; Ayaz, et al., 2019; Bas & Beyhan, 2010; Bulu & Yildirim, 2008; Demir, 2019; Duman & Yavuz, 2018; Erdoğan & Dede, 2015; Gülbahar & Tinmaz, 2006; Cirit-Işikligil & Günay, 2022; Ekizer & Yildirim, 2023; Yilan & Konca, 2021; Saricaoglu & Geluso, 2020; Ürün et al., 2014; Yuzlu & Dikilitas, 2021; Kemaloglu-Er & Sahin, 2022; Şahin & Kiliç, 2023
UAE	Alami, 2014; Nunn et al., 2015; Wyatt & Nunn, 2019

*Note that multi-country studies are reported in each relevant country in Table 1.

3.2. RQ#2: Implementation of PBLL in MENA PBLL research and its impact on learning of language form and function

3.2.1. RQ#2: PBLL Implementation and effectiveness

In all the 61 studies, PBLL was consistently found to enhance student engagement, motivation, and language skills within the various MENA contexts. In Algeria, for instance, Boudersa and Hamada (2015) reported that PBLL increased students' engagement and practical application of knowledge. In Egypt, Shaalan (2020) found that PBLL played a major role in developing dental vocabulary among ESL students by creating a more interactive, student-centered learning environment. Similarly, in Egypt, Helwa (2021) found that Multiple Intelligences-supported PBLL improved EFL receptive skills and learning satisfaction using digital tools. In Egypt's neighboring country, Libya, Garib (2022) and Suwaed (2022) provided further evidence of PBLL's effectiveness. Garib (2022) explored Technology-Assisted Project-Based Language Learning (TAPBLL) across Lebanon, Libya, and Syria, finding that despite challenges like technology access and curriculum integration, TAPBLL enhanced learning autonomy, real-world connections, and reduced teacher workload. Suwaed (2022) focused on raising environmental awareness through PBLL among Libyan EFL undergraduate students, demonstrating improvements in English language skills, content knowledge about the environment, soft skills, autonomy, and self-confidence.

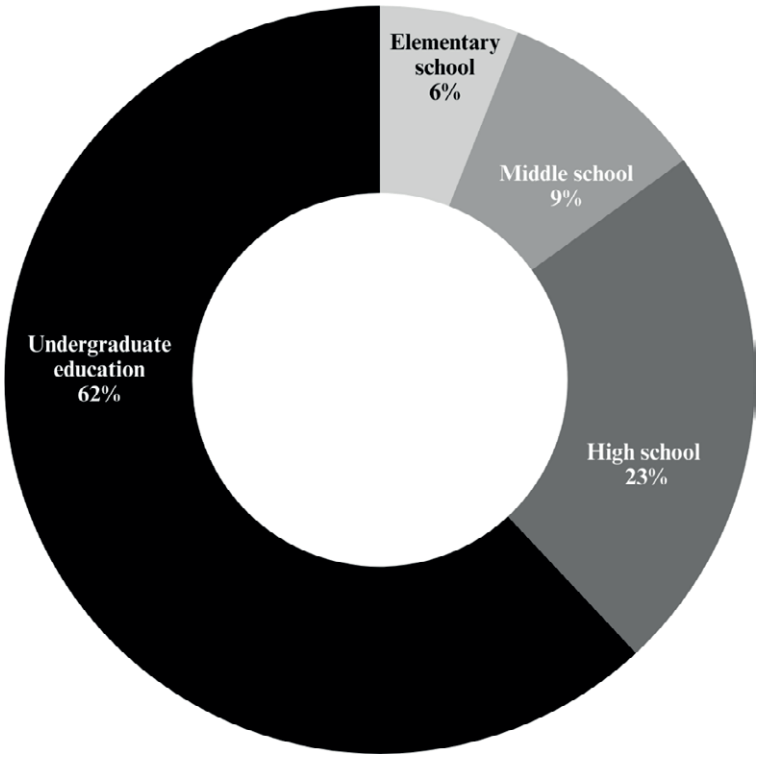

Figure 7. Distribution of education levels in MENA PBLL studies.

A broader range of studies in Iran (e.g., Maftoon et al., 2013; Moghaddas & Khoshsaligheh, 2019) highlighted PBLL's positive impact on motivation, cognitive development, and language skills, as is the case for studies in Turkey. In Iraq, Kavlu (2017) noted improvements in English language proficiency and 21st-century skills such as critical thinking and teamwork due to PBLL. In Jordan, both Alzu'bi and Sabha (2013) and Bataineh (2020) found that PBLL improved writing and speaking skills using mobile-based email and Web 2.0 tools. Studies in Kuwait (Alshuraiaan & Almefleh, 2023; Koushki, 2019; Milad, 2022), Saudi Arabia, Qatar, and UAE further reinforced PBLL's efficacy in various educational settings. In Qatar, Saliba et al. (2017) used PBLL to enhance information literacy and research skills among pre-medical students, while Du et al. (2019) study of elementary EFL classrooms explored how newspaper PBLL projects, supported by digital tools, improved language, personal, interpersonal, and affective skills. In Saudi Arabia, Alsamani and Daif-Allah (2016) showed vocabulary gains in ESP classes; Alotaibi (2020) enhanced persuasive writing in secondary students and Khodary et al. (2017) found Edmodo-supported PBLL fostered self-directed learning. In the UAE, Alami (2014) demonstrated improved student communicative competence through literature-based PBLL, and Wyatt and Nunn (2019) highlighted how PBLL in engineering communication courses fostered teamwork, critical thinking, and communication skills through a socially-situated, community-of-practice approach. Surprisingly, such benefits were also highlighted in under-resourced contexts such as the Palestinian Territories, where Migdad et al. (2021) found that third-grade students in Gaza improved their vocabulary acquisition with PBLL compared to traditional methods. More recently, Bakeer et al. (2023), in the West Bank, showed that combining PBLL with smartphone technology enhanced undergraduate EFL students' speaking skills, self-confidence, and engagement. Many of these studies recommended

integrating PBLL with modern technology for more effective and engaging language learning, which segues into the next theme technology integration into PBLL.

3.2.2. RQ#2: PBLL fostering language form and function

While not directly addressed in some studies, the language form and function theme emerged repeatedly in the collected studies in line with Beckett et al. (2020b), where PBLL had impacted both students' structural and practical use of English language, which facilitated students' grasp of grammatical structures and their ability to use language effectively in real-life contexts. For instance, in Algeria, Boudersa and Hamada (2015) found that PBLL increased student engagement and practical application of knowledge, improving both language form and function through structured learning of content where grammatical accuracy is implicitly emphasized and the functional aspect was "*to help students apply the knowledge gained inside the classroom by applying it on their own in other different, but related, situations*" (p. 35). In Egypt, Shaalan (2020) emphasized PBLL's role in the development of learners' dental vocabulary, highlighting improvements in language form, while Helwa (2021) reported enhanced EFL receptive skills through Multiple Intelligences-supported PBLL, showcasing both form and function. However, these studies failed to explicitly make a direct connection between students' learning of language form and function through PBLL. Instead, they focused on the traditional approach of examining the learning of the language form rather than its practical application.

In Iran, a few studies (Alavinia & Qoitassi, 2013; Shafaei & Rahim, 2015) reported that PBLL improved vocabulary acquisition and retention, enhancing language form. However, more recent studies, such as Bagherkazemi and Zahed Shekarabi (2023) examined students' learning of form and function through PBLL and emphasized that "*learning should be project-based as project accomplishment guarantees focus on meaning rather than form*" (p. 452). Bagherkazemi and Zahed Shekarabi further added that PBLL, when integrated into the Neurolinguistic Approach (NLA), can impact students' learning of language form and function, particularly in the development of both implicit and explicit grammar knowledge.

Parsaiyan and Gholami (2023) stressed the issue of form and function in Iran's English language education. They noted that, like other EFL settings, the emphasis on test-driven, teacher-centered, memorization-based, and traditional grammar-focused methods in the Iranian public sector has greatly limited opportunities for using English in real-life situations and for developing practical, self-directed learning strategies. This emphasis reflects how governmental fundings on English textbooks and classroom practices fail to provide students with activities that extend beyond the textbook content. As a result, Parsaiyan and Gholami found that students had difficulty moving from traditional learning practices such as rote learning and memorization to PBLL-related practices such as inquiry and autonomy, initially finding the new learning approach "confusing, even frustrating."

To examine the effects of PBLL on learning word structure and function, Reisi and Saniei (2016) found that learners who used word webbing with PBLL outperformed those who did not. This highlights the effectiveness of combining structured vocabulary learning with practical, functional use of language. Reisi and Saniei added that PBLL "*can give the students the opportunity to practice their understanding of the instructed words through interacting and communicating with their peers in the groups*" (p. 1195), aligning with Shafaei and Rahim (2015).

Kavlu (2017) in Iraq noted improvements in both grammatical competence (form) and communicative abilities (function) through PBLL since this approach fosters "*authentic language materials and*

improves communication skills" (p. 77). Jordanian researchers, Alzu'bi and Sabha (2013) and Bataineh (2020), reported enhancements in writing and speaking skills, addressing both structural and practical language aspects. Furthermore, in Kuwait (Milad, 2022) and Libya (Suwaed, 2022), PBLL was found to enhance both language skills and student engagement. The theme extends to Lebanon (Garib, 2022), and Morocco (Bouqetyb, 2021) that highlighted improvements in speaking skills and real-life application. Oman's studies (Al-Busaidi & Al-Seyabi, 2021; Belwal et al., 2021) indicated improved English proficiency in both form and function. In the Palestinian Territories, Bakeer et al. (2023) and Migdad et al. (2021) reported improvements in speaking skills and vocabulary acquisition through smartphone-integrated PBLL, showcasing language form in its functional use. In Qatar (Du et al., 2019; Saliba et al., 2017) and Saudi Arabia (Alotaibi, 2020; Alsamani & Daif-Allah, 2016) stressed that PBLL's effectiveness in enhancing advanced research skills and persuasive writing, addressing both form and function in academic contexts. Assaf (2018) in Syria found improvements in linguistic skills and communication abilities through PBLL, while extensive research in Turkey (e.g., Avci & Adiguzel, 2017; Gülbahar & Tinmaz, 2006) highlighted PBLL's role in improving functional language via tools like WhatsApp.

3.3. RQ#3: Challenges and technology tools commonly mentioned in the PBLL MENA studies in well-resourced and under-resourced contexts.

3.3.1. RQ#3: Challenges implementing PBLL

Despite the positive outcomes, all 61 studies highlighted challenges to PBLL implementation. One common challenge among 54 studies is the need for teacher training. For instance, in Algeria, Boudersa and Hamada (2015), who identified issues with teacher project assessment and time constraints, concluded that since project work "*needs due attention and follow up to achieve the intended goals*" (p. 29), authentic assessment techniques and more support and resources for teachers are needed. In Iraq, Kavlu (2017) noted the need for extensive planning and teacher training to overcome resistance to student-centered approaches because "*if teachers are not properly trained..., they might not be able to help their students learn*" (p. 72) through project work. In the same vein, Suwaed (2022) added that "*in-service training courses should be provided for teachers because PBL is still a new method of teaching and not yet familiar to most Libyan EFL teachers*" (p. 120). Due to the urgent need for teacher training, Bakeer et al. (2023) proposed that educational institutions impose "*compulsory workshops and training courses*," hoping that this would result in a "*cascading knowledge*" effect (p. 84).

Similarly, in Lebanon, Libya, and Syria, Garib (2022) reported disruptive challenges like technology access, restrictive curriculum, and assessment issues, emphasizing the need for teacher training and contextual adaptation. Most of the studies (88.52%) across the region called for teacher professional development and structured support to maximize the benefits of PBLL. For instance, Al-Busaidi and Al-Seyabi (2021) in Oman recommended providing more examples of successful projects and structured support to improve course design skills. Ekizer and Yildirim (2023) concluded that in Turkey there is a "*need for schools to invest in technology and to provide training for teachers*" to effectively integrate PBLL (p. 126). In Saudi Arabia, several studies (e.g., Alsamani & Daif-Allah, 2016; Khodary et al., 2017) emphasized the need for better technological support and professional development to sustain PBLL's positive impacts.

In Morocco, Bouqetyb (2021) highlighted the lack of technological tools and insufficient teacher support as major barriers to effective PBLL implementation stating that "*time constraints, the number of students, students' linguistic competence, and the necessity to follow the textbook are obstacles that hin-*

der the use of project work" (p. 470). Commitment to the curriculum was another major challenge for teachers to innovate––such restrictions leave no room for teachers to create interactivity for students. Even in well-resourced countries, such as Qatar, Du et al. (2019) stressed that PBLL is viewed as "*an add-on to other curricular requirements*" (p. 13), which reflects the cultural resistance to incorporating any teaching methods not explicitly dictated by the curriculum. In Turkey, the issue with the curriculum was summed up by Ayaz et al. (2019), who stated that "*high schools in Turkey suffer from various challenges regarding the implementation of the curriculum...in practice, though everything seems to be quite successful in theory*" (p. 53).

3.3.2. RQ#3: Technological integration into PBLL

Of the 61 PBLL studies, 13 studies did not integrate technology into their projects, including one in Algeria (Boudersa & Hamada, 2015), one in Egypt (Shaalan, 2020), five in Iran (Maftoon et al., 2013; Nafissi et al., 2020; Pourmandnia et al., 2021; Reisi & Saniei, 2016; Sadeghi et al., 2016), one in Kuwait (Koushki, 2019), one in Palestinian Territories (Migdad et al., 2021), one in Saudi Arabia (Almulla, 2020), one in Tunisia (Trabelsi, 2013), one in Turkey (Bas & Beyhan, 2010), and one in the UAE (Alami, 2014). The remaining majority (n=48) reported that technology played, to varying degrees, a crucial role in enhancing the effectiveness of PBLL in their project implementation. For example, in Iran, Alavinia and Qoitassi (2013) used SMS technology to improve vocabulary acquisition, while other studies incorporated tools like WhatsApp, wikis, blogs, and online courses (e.g., Arabloo et al., 2021; Nami, 2022; Parsaiyan & Gholami, 2023).

When comparing the technological integrations in well-resourced contexts with under-resourced in MENA, interesting findings emerged. The expected finding was that well-resourced contexts used more advanced technologies, whereas the under-resourced contexts used basic technologies. What is interesting, however, is that under-resourced contexts repurposed particularly low-bandwidth apps such as SMS, mobile phones, basic online forums, and mobile-based applications like WhatsApp, Facebook Messenger, Microsoft Office to overcome internet access issues (see Tables 2 and 3). For instance, social media apps were commonly used as LMSs to facilitate student-student and teacher-student interaction, submission of project components, project showcases, among others.

While "*the lack of technology is one of the most severe challenges that hamper the use of project work*" (Bouqetyb, 2021: p. 462), the studies that incorporated technology reported that these tools added interactivity and enriched the learning process. For instance, Bakeer et al. (2023) found that integrating PBLL with smartphone technology and social media tools improved students' speaking skills and engagement, as it encouraged students to collaborate in and out of the class. Similarly, Du et al. (2019) emphasized the role of digital technology in implementing PBLL in EFL classrooms, though teachers had to adapt to contextual challenges.

Table 2 shows common reliance on WhatsApp and Facebook Messenger/Groups as LMSs while other technologies were described vaguely as computers and Internet access. To compare these tools with well-resourced contexts, see Table 3.

As outlined in Table 3, the technologies used for project implementation in well-resourced countries included more advanced technologies such as LMS, Smartboards, advanced software for animations and e-portfolios, Web 2.0 tools, digital platforms like Google Classroom, Atlas, among others. Notably, of all the well-resourced countries, WhatsApp was used in three studies, all in Turkey, and specifically focused on examining WhatsApp for learning with PBLL.

Table 2. PBLL technologies used in Algeria, Egypt, Iran, Iraq, Jordan, Lebanon, Libya, Morocco, Palestinian Territories, Syria, Tunisia.

Studies	Technology Used	Studies	Technology Used
Helwa, 2021	WhatsApp, Microsoft Teams, Zoom	Hekmati, 2022	Online class, Adobe Connect software
Alavinia & Qoitassi, 2013	SMS (Mobile phones), ebooks.	Kavlu, 2017	Electronic devices, mobile phones
Moghaddas & Khoshsaligheh, 2019	Internet, online forum	Alzu'bi & Sabha, 2013	Mobile-based email
Mohamadi, 2018	Internet, online forum	Bataineh, 2020	YouTube, Facebook Messenger, Weebly, Wikipedia
Shafaei & Rahim, 2015	Computers, Internet	Mirza & Halabi, 2021	Computers, mobile phones, survey questionnaire
Arabloo et al., 2021	WhatsApp, wikis, blogs, Word, dictionary apps	Garib, 2022	WhatsApp, Facebook
Bagherkazemi & Zahed Shekarabi, 2023	Online (unspecified technology)	Suwaed, 2022	Internet, presentations, video production
Nami, 2022	WizIQ, online courses, technology-review projects	Bakeer, Dweikat, & Smith, 2023	Smartphones, social media (Messenger, WhatsApp)
Parsaiyan & Gholami, 2023	Internet, WhatsApp, SHAD app	Assaf, 2018	Video-making equipment, WhatsApp, Facebook
Shiraz & Larsari, 2016	Computers, Internet	Bouqetyb, 2021	Internet

The advanced tools were used to facilitate interactivity, multimedia use, and sophisticated affordances for project work, which reflects how advanced contextual infrastructure can diversify teachers' choices and practices to encourage student innovation and creativity. In contrast, the reliance on low-bandwidth applications in under-resourced settings, while limiting, highlights the resilience, adaptability, and resourcefulness of teachers in these regions. As Garib (2022) stated, contextual "*challenges forced the teachers to repurpose the use of technology, leading them to adapt alternative methods, such as WhatsApp, and making inaccessible technologies accessible via VPN. This type of perseverance exemplifies: 'where there is a will, there is a way!*" (p. 1454). Despite teachers' grit, there surely is a digital divide between the well-resourced and under-resourced countries. Nevertheless, the findings presented in this section exhibit the many positive impacts of educational technology on students' learning through PBLL. They also show the affordances of technology tools for implementing innovative educational approaches such as PBLL helping teachers and students to teach and learn creatively and expansively. With digital literacy training, teachers and students can utilize technology tools, especially GenAI tools, to generate project ideas, plan projects in alignment with content curriculum standards, project implementation, and project reports, multimodally addressing the time issue and managing the complex nature of projects efficiently, effectively, and holistically. They can also utilize GenAI to create assessment instruments for their projects to bridge the gap identified in our review.

4. Discussion

The current systematic review of PBLL studies in the MENA region provided the depth and breadth of unique practices in the region. This discussion synthesizes the key findings with the themes explored in the literature review.

Table 3. PBLL technologies used in Kuwait, Oman, Qatar, Saudi Arabia, Turkey, UAE.

Studies	Technology Used	Studies	Technology Used
Milad, 2022	LMS, PowerPoint/Prezi, Kahoot, Quizlet, Grammarly	Duman & Yavuz, 2018	Internet, websites
Alshuraiaan & Almefleh, 2023	General reference to digital resources	Erdoğan & Dede, 2015	Computer technologies (software for portfolios, Word, PPT)
Al-Busaidi & Al-Seyabi, 2021	PowerPoint presentations	Gülbahar & Tinmaz, 2006	Animation software, e-portfolios
Belwal. et al., 2021	Atlas.ti 8, mobile apps	Cirit-Işikligil & Günay, 2022	Web 2.0 tools (Zoom, WhatsApp, Discord, Skype)
Du et al., 2019	Digital technology, mobile devices, online resources	Ekizer & Yildirim, 2023	Online platforms and digital tools (LMS, social media, Google Docs, Zoom)
Alotaibi, 2020	Videos, blogs	Yilan & Konca, 2021	Google Classroom, digital platforms
Alsamani & Daif-Allah, 2016	Computers and online resources	Saricaoglu & Geluso, 2020	Skype, FaceTime, WhatsApp, Facebook Messenger, multiple apps, computers, phones
Khodary et al., 2017	Edmodo	Duman & Yavuz, 2018	Internet, websites
Madkour, 2016	Multimedia tools, OmegaT (machine translation software)	Nunn et al., 2015	Video-recordings
AlMulhim & Eldokhny, 2020	Internet, computers	Wyatt & Nunn, 2019	Internet
Ayaz et al., 2019	Smart boards	Saliba et al., 2017	LMS, online presentations, video tutorials, digital resources
Bulu & Yildrim, 2008	Online platform (LTTS), communication tools	Avci & Adiguzel, 2017	WhatsApp
Demir, 2019	Digital technology, internet	Yuzlu & Dikilitas, 2021	Dictionaries, picture dictionaries, translation apps, websites, and word walls with bilingual terms/visuals
Kemaloglu-Er & Sahin, 2022	Internet, videos, English texts online, smart boards, PowerPoint presentations, eTwinning platform, and Skype	Şahin & Kiliç, 2023	Distance education platform and Google Classroom

The literature highlights the role of PBLL in enhancing student engagement and motivation (Beckett, 1999; Slater & Beckett, 2019; Thomas, 2000). Such impacts of PBLL align with the findings across several MENA studies, as pointed out in the PBLL implementation and effectiveness theme. For instance, several studies (e.g., Boudersa & Hamada, 2015; Kavlu, 2017) reported that PBLL increased students' engagement and interest in their learning. Other research (Bataineh, 2020; Bouqetyb, 2021; Helwa, 2021; Shafaei & Rahim, 2015; Suwaed, 2022) found that PBLL enhanced students' learning experiences and boosted their language use and autonomy, aligning with the literature's emphasis on learner autonomy and interactive learning environments despite challenges (Guo, 2006). While a handful of studies directly addressed PBLL's impact on language form and function (e.g., Bagherkazemi & Zahed Shekarabi, 2023; Parsaiyan & Gholami, 2023), the majority did not explicitly examine these aspects, which leads back to Beckett et al.'s (2020b) emphasis on the scarcity of research on language form and function within PBLL, and MENA is no exception.

Besides the positive impacts of PBLL, implementing this approach in MENA poses challenges. The literature shows that the MENA region's economic status, political instability, educational infrastructure,

technological inaccessibility, and restrictive curricula can negatively affect the implementation of educational innovations like PBLL (Nasr & Wilby, 2017; Rahme & Altamimi, 2022; Romanowski & Karkouti, 2021). This review identified similar barriers, such as the need for teacher training, curriculum constraints, and limited technological resources (e.g., Boudersa & Hamada, 2015; Farag & Yacoub, 2023; Garib, 2022; Hayes, 2012; Kavlu, 2017; Suwaed, 2022). Such challenges echo Beckett's (2024; 2025), Beckett et al.'s (2020b) and Beckett and Pae's (2024) raised concerns for needing adequate teacher training and support for PBLL practices. Without training or support, these challenges impede the progress of ELT. Moreover, the literature emphasizes the adaptability of PBLL to different educational and cultural contexts (Kelsen, 2018; Sato & Horne, 2020; Wang, 2020). This review found that MENA teachers adapted PBLL to fit their specific contexts, often repurposing low-bandwidth technologies like WhatsApp and Facebook Messenger to facilitate project work (Bakeer et al., 2023; Garib, 2022). This innovative use of technology, despite resource limitations, demonstrates the flexibility and resilience of educators in the region.

The integration of technology into PBLL, as found in this review, aligns with global practices where digital tools are used to enhance learning experiences (Alavinia & Qoitassi, 2013; Nami, 2022). The studies highlighted the importance of technology in facilitating interactive and engaging learning, even in under-resourced contexts (Bakeer et al., 2023; Du et al., 2019). Such findings support the literature's claim that PBLL can be tailored to available resources effectively, thereby enhancing its applicability in diverse settings (Beckett et al., 2020b; Beckett & Miller, 2006; Thomas & Yamazaki, 2021). Beckett et al. (2020b) speculated that technology-mediated PBLL can be effective in diverse settings, and with the current findings, it is also possible with limited resources. Therefore, findings of this study spoke to Beckett et al.'s concerns and showed their proposals for PBLL adaptability and technology integration to be viable in all contexts. However, while this review reported MENA's increasing research interests in PBLL, more research is needed in both under-resourced and better-resourced MENA countries. Future reviews could focus on reviewing articles published in languages other than English and housed in databases other than the ones used in the current study. Additionally, the current findings revealed that 54 studies analyzed stated the need for teacher training, suggesting that MENA teacher professional development programs are urgently needed due to the overwhelming demands and calls.

Besides these pedagogical and infrastructural considerations, the current study also highlights a methodological innovation in the use of GenAI in qualitative research analysis. Even though this study carefully accounted for GenAI hallucinations in the analysis process, another area for further exploration that is deserving of attention is considering the potential for bias in GenAI's interpretation of qualitative data. For example, although the use of ChatGPT was human-led and cross-validated with NVivo in the current study, it is important to acknowledge that GenAI models could potentially produce varying thematic outcomes, even when analyzing the same dataset. Such differences may occur due to variations in the training data, algorithms, or even simply prompt interpretation (Chapelle, 2025; Garib, 2024). Therefore, future research could benefit from comparing multiple GenAI models to evaluate the thematic consistency and explore how interpretative bias might influence the outcomes of AI-assisted analysis, which could also add further depth to the reliability and validity of the assessment of AI-assisted qualitative research practices.

5. Conclusion and future directions

As with other parts of the globe, PBLL can enhance language learning in the MENA region. However, the challenges identified highlight the need for ongoing support, professional development, and

infrastructural improvements for effective PBLL implementations. Teachers need practical training and enough resources to navigate their contextual challenges. Additionally, addressing technological limitations and curriculum constraints is another step forward to 'free' teachers from their restrictive curriculum requirements, which in turn, can encourage more innovative and interactive learning. By investing in these areas, the definition of learning for MENA students can be fundamentally transformed. Such investments will empower teachers to implement more effective projects while providing students with more meaningful and relevant educational experiences. This shift towards a more interactive approach to language learning will equip MENA students with critical thinking, creativity, collaboration, communication, and competencies in digital literacy necessary for success in the 21st century (Beckett, 2023).

6. References

(* refers to the studies used in our systematic review)

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Museums for all: Perspectives of Special Pedagogy for inclusion

Musei per tutti: prospettive di Pedagogia Speciale per l'inclusione

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Abstract Accessibility to cultural heritage represents a fundamental right for social inclusion (United Nations, 2006). It is a key principle to eliminate barriers and ensure the inclusive enjoyment of cultural experiences. Within this frame, in this paper, we will discuss how digital technologies, such as Augmented Reality (AR), Virtual Reality (VR), and Artificial Intelligence (AI), offer innovative solutions to meet the specific needs of people with disabilities, facilitating access and enriching the visitor experience. Specifically, this paper outlines a project undertaken by the Special Pedagogy research group at the University of Macerata to enhance the inclusivity of museum environments for people with intellectual disability and autism through the use of digital technologies. The findings highlight how the combined use of AR, VR, and AI fosters cultural participation and improves the well-being of people with disabilities, reinforcing the role of museums as inclusive spaces for learning and engagement.

KEYWORDS Museum Accessibility; Special Pedagogy; Technological Innovation; Intellectual Disability; Autism.

Sommario L'accessibilità al patrimonio culturale rappresenta un diritto fondamentale per l'inclusione sociale (ONU, 2006), diventando il principio chiave per eliminare le barriere e garantire una fruizione inclusiva delle esperienze culturali. In questa cornice, verrà discusso come le tecnologie digitali, quali la Realtà Aumentata (AR), la Realtà Virtuale (VR) e l'Intelligenza Artificiale (AI), offrano soluzioni innovative per soddisfare le esigenze specifiche delle persone con disabilità, facilitando l'accesso e arricchendo l'esperienza dei visitatori. Nello specifico, il presente lavoro illustra un progetto intrapreso dal gruppo di ricerca di Pedagogia Speciale dell'Università di Macerata, per migliorare l'inclusività degli ambienti museali per le persone con disabilità intellettiva e Disturbo dello Spettro Autistico attraverso l'uso di tecnologie digitali. I risultati evidenziano come l'uso combinato di AR, VR e AI favorisca la partecipazione culturale e migliori il benessere delle persone con disabilità, rafforzando il ruolo dei musei come spazi inclusivi per l'apprendimento e il coinvolgimento.

Parole chiave Accessibilità Museale; Pedagogia Speciale; Innovazione Tecnologica; Disabilità Intellettive; Disturbo dello Spettro Autistico.

1. Introduction

Accessibility to cultural heritage constitutes an indispensable right recognized as central to full social inclusion. This principle, enshrined in international treaties (United Nations, 2006), reflects

two complementary dimensions, namely physical accessibility to cultural places (Art. 9a) and cultural accessibility to content and experiences (Art. 9b). It suggests the role of accessing cultural heritage as an educational tool (Di Rosa, 2024; Jagielska-Burduk et al., 2021; Muscarà & Romano, 2021) as well as its potential impact on the general well-being of the person (Giaconi, 2015; Schalock & Verdugo Alonso, 2002, 2007) by fostering their active involvement and participation (World Health Organization, 2001).

In the museum field, innovative perspectives in the design of spaces and programs dedicated to ensuring accessibility, usability and inclusive enjoyment of cultural heritage have been consolidated over time (Bortolotti & Mastrogiuseppe, 2019; Gordon et al., 2016; Mace, 1985; Steinfeld & Maisel, 2012). These approaches identify adaptations to formal and informal contexts to reduce possible barriers between people and environments. Among them, Universal Design (UD) (Mace, 1985, 1997; Story et al., 1998) and Universal Design for Learning (UDL) (Gordon et al., 2016; Rose, 2000), focus on design that integrates flexibility and accessibility from the planning stage (Rappolt-Schlichtmann et al., 2013) to respond to the needs of an increasingly heterogeneous population. In this regard, the literature (Bortolotti & Paoletti, 2021; Gordon et al., 2016; Savia, 2016; Shogren et al., 2022) highlights how in the design of museum interventions considering variables such as expectations, cultural background and learning styles can produce positive results in terms of participation, engagement and involvement (D'Angelo et al., 2024; Garcia Carrizosa et al., 2020; Gordon et al., 2016; Münch et al., 2022). A further element of innovation is the integration of such approaches with technological tools, a combination that allows not only the adaptation of content to different needs but also the expansion of channels of access to information (Dudley et al., 2023; Giaconi et al., 2021; Shehade & Stylianou-Lambert, 2020). Technologies such as Virtual Reality (VR), Augmented Reality (AR) and Artificial Intelligence (AI) offer the possibility of designing immersive and multisensory experiences capable of breaking down barriers and facilitating the inclusive enjoyment of cultural heritage.

This paper highlights ways these approaches can be used to design an inclusive museum experience, promoted by the research group in Didactics and Special Pedagogy at the University of Macerata. We specifically describe an investigation of how AR and VR technologies can be valuable tools to respond to the need for anticipation in the exploration of the museum space by people with autism, as well as how Artificial Intelligence can be a means of support for the creation of accessible museum captions in Easy-to-Read language.

2. Innovative technologies for inclusion

The concept of accessibility, as highlighted by the Special Pedagogy literature (Besio et al., 2023; Bortolotti & Paoletti, 2021; D'Angelo et al., 2024; Friso & Marchesani, 2022; Giaconi et al., 2023; Gimenez & Thomas, 2015; Greco, 2019; Pinnelli & Fiorucci, 2023; Straniero, 2023) necessitates in-depth reflection by cultural institutions on the usability of information and content to provide concrete opportunities for exploration, learning and engagement, particularly for people with disabilities. Specifically, we are going to focus on the evidence emerging from the literature on the merit of cultural and physical accessibility for people with autism and intellectual disabilities.

Scientific findings have highlighted that people with autism may need support with creating anticipatory models that can support them with predicting future experiences and actions (Barale et al., 2009), such as fluidly understanding the meaning of interpersonal exchanges or ongoing events, as there is a tendency to focus more on details (Giaconi, 2015; Happé & Frith, 2006). In fact, people with

autism often exhibit a detail-focused processing style, which results in a particularly attentive and analytical view of individual elements as opposed to the overall context (Giaconi, 2015). Considering this, technologies such as Virtual Reality and Augmented Reality can be rather promising tools for fostering museum accessibility. The complexities related to the creation of anticipatory models (Barale et al., 2009) can be supported by the use of technological solutions that offer visual anticipation of spaces and experiences. VR, for example, makes it possible to simulate the exploration of museum environments in a controlled and predictable context, allowing people with autism to familiarize themselves with places before the actual visit (Campitiello et al., 2022; Del Bianco et al., 2024; Drageset & Crippen, 2024; Giaconi et al., 2021). This type of experience allows for increased spatial understanding, providing a clear view of the temporal sequences and events that will follow, facilitating adaptation to new environments. AR, on the other hand, can enrich the museum experience through the overlay of visual information that guides the user and provides anticipation of objects or events taking place, allowing the user to focus on relevant details without losing the overall context. In addition, the use of AR devices also reduces sensory load by offering information in a customizable mode (e.g., with magnified text, modulated sounds, and specific colours), responding to the needs of each visitor (Campitiello et al., 2022; Hutson & Hutson, 2023).

When supporting people with intellectual disability, the relevant literature (Schalock, 2010; Wehmeyer et al., 2008) suggests the importance of considering support needs related to difficulties in processing abstract concepts and accessing complex information, especially in handling articulate texts, interpreting verbal and visual content and assimilating concepts that require some level of abstraction or critical thinking (Mayer, 2021; Poncelas & Murphy, 2007). Such challenges can, therefore, hinder full participation in cultural, educational and social experiences, including visiting museum spaces, where content structuring usually involves dealing with elaborate and often abstract information. In this direction, studies (Mayer, 2021; Poncelas & Murphy, 2007) show how it is possible to promote the full accessibility of knowledge and information through clear and easy-to-understand formats. In this regard, the Easy-to-Read guidelines (Bernabé Caro & Orero, 2019; Fajardo et al., 2014; Freyhoff et al., 1998; Madina et al., 2023; Nomura et al., 2010; Tronbacke, 1997) fit into this perspective, facilitating complex concepts through customized paths that meet individual communication needs. This adaptability is embodied in diversified modes of communication (e.g., written, audible, simplified tools and formats, human or alternative readers) that are aligned to the support needs of people with intellectual disability (Bortolotti & Paoletti, 2021).

As highlighted in the literature (Bernabé Caro & Orero, 2019; Fajardo et al., 2014; Madina et al., 2023; Nomura et al., 2010), adopting Easy-to-Read guidelines is a key element in fostering the acquisition of new skills, promoting knowledge exchange, encouraging active participation, and ultimately increasing self-determination (D'Angelo et al., 2024; Del Bianco et al., 2019; Fajardo et al., 2014; Shogren et al., 2022). In this context, technological tools such as Artificial Intelligence can support the enhancement of accessibility to museum content by facilitating the process of adapting information into Easy-to-Read formats (Aliseda et al., 2023; D'Angelo et al., 2024; Olmedo-Pagés & Arquero-Avilés, 2024). AI can accelerate the process of making text more accessible, enabling complex cultural content to be transformed into clear and understandable language, thereby avoiding ambiguity and reducing reading difficulty. The use of AI in creating Easy-to-Read content can also involve generating visual descriptions for complex concepts through the combination of images, icons, and symbols, making the information more easily understandable and increasing the efficiency of the process, rather than substituting it (D'Angelo et al., 2024).

These technologies can be leveraged to create various possibilities for interacting with the museum environment and activities that address specific personalization needs (D'Angelo et al., 2024; Hutson & Hutson, 2024; Kasemsarn et al., 2024). In this direction, we will present in the next section a path to design an accessible museum environment through innovative and technological solutions, with the co-participation of people with disabilities. After describing the research design and the activities, we will share the process carried out to customise the museum visit. We will focus specifically on co-designing paths with people with autism to build customized itineraries and thematic paths through AR and VR, and on creating paths with people with intellectual disabilities to experience museum captions in Easy-to-Read language through the support of Artificial Intelligence.

3. The research protocol

In line with regulatory provisions on the renewal of museum accessibility and inclusion plans mandated in 2018 by the Ministry for Cultural Heritage and Activities (Ministero per i beni e le attività culturali, 2018) and in continuity with previously conducted studies (D'Angelo et al., 2024; Del Bianco et al., 2024; Giaconi et al., 2021; Giaconi et al., 2023), the research group of the Chair of Pedagogy and Special Education at the University of Macerata, in the biennium 2022-2024, undertook a project aimed at making the museum experience more accessible and inclusive for all visitors, with particular attention to people with autism and intellectual disability.

This initiative is situated within a theoretical and methodological framework favouring a participatory approach (Cornwall & Jewkes, 1995) based on co-designing with people with disabilities at every stage of the process, from planning to developing and implementing the museum layout to testing the accessible and inclusive museum itineraries. This methodology made it possible to enhance the expertise of people with autism and intellectual disability and the research team, integrating their contributions into the definition of accessibility strategies. The decision to co-design with people with disability allowed the synergy of different skills in creating an inclusive museum context responsive to the real needs of all visitors.

Based on these assumptions, the participatory research was articulated concerning the following procedural steps (Table 1) (D'Angelo et al., 2024; Giaconi et al., 2023):

Table 1. The research procedure.

Phase 1. Mapping of critical issues related to accessibility, both physical and cultural, of the museum context involved in the project (6 months);
Phase 2. Co-design and development of integrated technological solutions to make museum spaces usable and develop accessible and inclusive paths (12 months);
Phase 3. Re-testing of the implemented solutions (6 months).

Respecting these phases, two parallel macro-pathways were articulated to move forward with addressing identified issues critical to accessibility, both physical and cultural (Giaconi et al., 2023):

– "Pathway a": involved co-design with people with autism to create predictable environments through integrated VR and AR technological solutions;
– "Pathway b": involved co-designing with people with intellectual disability to create accessible captions in Easy-to-Read language via AI technological solutions.

Two research teams were formed to address these distinct but related pathways. The research team that dealt with "Pathway a" involved an interdisciplinary team composed of museum experts, Special Pedagogists, Virtual and Augmented Reality experts and five university students with autism. "Pathway b", on the other hand, was curated by the teamwork of engineers, museum experts, Special Pedagogists and people with intellectual disabilities experts on Easy-to-Read affiliated with different associations from the Marche Region. This collaborative and interdisciplinary approach allowed for the development of a constant dialogue between theory and practice, ensuring that the proposed solutions aligned with the real needs of museum visitors.

3.1. "Pathway a"

"Pathway a" aimed to develop immersive and innovative environments for multimodal interaction, implemented with the support of people with autism using the methodology of participatory research; for this reason, the experimental procedure consists of the following activities:

1. Visit to the museum and data collection:
   1.1 Selection of the museum's relevant cultural contents and information made by a joint team of museum experts, Special Pedagogists, Virtual and Augmented Reality experts, and people with autism;
   1.2 Data collection activity conducted by the team of VR professionals to create the museum's virtual objects and spaces.
2. Observation and data collection concerning barriers and facilitators of the museum:
   2.1 Conduction of structured interviews with people with autism regarding their museum experience;
   2.2 Interview analysis conducted through the Grounded Theory methodology.
3. Creation of the museum VR prototypes.
4. Test and retest phase with a control group of people with and without disabilities;
   4.1 Final adjustments.

Specifically, in Activities 1.1, the teamwork visited the museum multiple times in order to select the most relevant cultural content to be transposed in the VR environment.

In activity 1.2, the team of VR experts captured the main museum spaces in spherical photos through a 360° camera and uploaded the pictures to the Web[1] that were integrated and edited using specific tools and software such as Ricoh Theta Converter Pro, Retouch3, and Marzipano Tool, the latter based on an open-source library. The development of the spherical photos was followed by the creation of 3D models (Caldarelli, 2023; Ceccacci et al., 2021).

During Activity 2, as done in previous research (Campitiello et al., 2022; Giaconi et al., 2021; Shogren et al., 2022), interviews with people with autism regarding their museum experience (Activity 2.1) allowed the research team to outline the most relevant difficulties connected to the access and fruition of the museum heritage. The interview analysis followed the Grounded Theory methodology (Strauss & Corbin, 1994), allowing us to identify and organize the main accessibility and usability issues of the museum through labels (Activity 2.2). The analysis of the interviews allowed the iden-

[1] Various tools and software were used for the project, such as a Ricoh Theta SC2 spherical camera, a smartphone equipped with Android 6.0 OS, the Ricoh Theta S apps, Ricoh Theta Converter Pro, and Retouch3 and Marzipano Tool4 that is a free web service based on an open-source library.

tification of two main macro-categories (Giaconi et al., 2023): barriers and facilitators, specifically in relation to the sensory, cognitive, and communicative characteristics commonly associated with autism. These categories, discussed and refined, were essential in understanding how people with autism perceive and experience museum environments. The first macro-category, referring to barriers, was conceptualised as a "fragmented experience". This included difficulties such as limited access to content not tailored to different processing styles, incoherent or disconnected information across exhibits, and the abstract nature of certain content that lacked concrete support. Added to this was the unclear function of museum spaces, which often complicated spatial orientation. Together, these factors contributed to cognitive overload, disorientation, and a diminished sense of engagement. On the other hand, the facilitators were framed under the theme of "involvement", highlighting elements that promote active and meaningful participation. These included the presence of concrete and experiential content, the opportunity for visitors to make choices and personalise their pathways, the availability of interactive modes of engagement – often supported by technology – and the structuring of content through narrative frameworks that support understanding and orientation. These aspects were recognised as essential to fostering accessible, predictable, and inclusive museum experiences for people with autism.

In relation to these findings, concerning Activity 3, to ensure greater accessibility to cultural content, the prototype was designed considering supporting visual thinking and reality-anchored concepts (Ceccacci et al., 2021). Interactive VR features, such as scene switching and information popups containing multimedia content, were integrated to make the pathway customizable and easily interrogated by users. This process was a crucial step in creating a true-to-life virtual tour that allowed people with autism to explore museum environments, both outdoor and indoor, in advance, increasing the predictability and the anticipation of the spaces. The need for adherence to reality, typical of people with autism (Morgan et al., 2003), led us to implement the prototype with explanations of symbols, codes, and signs of the museum through the impression of augmented spherical and real images. Specifically, the virtual prototype was created following the principles of Equitable Use; Flexibility in Use; Simple and intuitive use; Perceptible information; Tolerance of error; Low physical effort; Size and space for approach and use (Story et al., 1998). Starting from these assumptions the interface, which is intuitive and conforms to the principles of Universal Design (Story et al., 1998), integrates tactile, vocal and visual inputs, enabling realistic and immersive interaction with virtual objects. These solutions, in addition to making the museum experience accessible to an increasingly diverse audience, can facilitate the design of educational activities both before and after the visit.

The prototype, developed in collaboration between experts and people with autism, was subsequently tested inside the museum (Activity 4). Five additional university students with no previous experience in the museum context were involved in the final validation phase. The feedback gathered from these new users helped verify the prototype's effectiveness and appropriateness on different possible levels. Final adjustments (Activity 4.1) were made in relation to inconsistencies and critical issues that were detected.

3.2. "Pathway b"

"Pathway b" aimed to create accessible captions in Easy-to-Read language using Artificial Intelligence systems (D'Angelo et al., 2024). Our goal was not to replace co-design with automated systems but rather to employ technology as a tool to make the process of adapting information into an accessible format more efficient. For these reasons, in line with the principles of the *Inclusion Europe* move-

ment[2], all stages of the process of transforming texts into Easy-to-Read format, including content verification and revision, actively involved people with intellectual disability as experts on Easy-to-Read. Adapting documents in Easy-to-Read language is a cyclical process and involves three procedural steps: analysis, transformation, and validation. Through these steps, the active involvement of people with intellectual disability as experts in Easy-to-Read allows the production of information that effectively meets accessibility criteria. However, such participation requires a significant commitment and use of human resources, so scholars have sought alternative solutions (Suárez-Figueroa et al., 2020). In this regard, several semi-automatic systems based on AI have been proposed. The most useful AI tool was initially evaluated, with special reference to Large Language Models. Among LLM systems, ChatGPT has shown promise in supporting tasks related to natural language processing (Araújo & Aguiar, 2023; Liu et al., 2023; Min et al., 2023), facilitating both the analysis of texts and their compliance with Easy-to-Read guidelines (Suárez-Figueroa et al., 2020; Uricchio et al., 2024).

Therefore, ChatGPT's level of knowledge regarding the Easy-to-Read guidelines (Min et al., 2023) was tested by analyzing the responses provided to 20 open-ended questions that ChatGPT answered freely without any predetermined structure. The questions were sent to different versions of ChatGPT (3.5 and 4.0) using the OpenAI API, with the support of a Python script. The results showed that ChatGPT 4.0 has superior knowledge of Easy-to-Read guidelines compared to version 3.5. Based on these observations, a specialized prompt was developed to guide ChatGPT 4.0 in producing texts adhering to the Easy-to-Read guidelines (D'Angelo et al., 2024). This prompt was structured into three main sections:

(a) a contextual description directing the model to behave as an accessibility expert;
(b) a detailed explanation of the Easy-to-Read guidelines;
(c) explicit instructions on how to apply these guidelines in simplifying texts.

The tool thus configured was used to create 10 simplified museum captions. These texts were then submitted to the interdisciplinary working group which rated their consistency with the guidelines by adopting a Likert scale of 1 to 5 (D'Angelo et al., 2024):

1) Completely incorrect – The text does not significantly meet the standards for facilitated comprehension.
2) Insufficiently correct – The text shows an attempt to align with the guidelines, but several key aspects are missing.
3) Sufficiently correct – The text meets the guidelines by ensuring a basic level of understanding.
4) More than sufficiently correct – The text adequately meets the guidelines' requirements but offers room for improvement.
5) Completely correct – The text fully and flawlessly adheres to the Easy-to-Read guidelines.

The initial evaluation of the texts generated using ChatGPT 4 indicated that 7 out of 10 captions reached an average level of "sufficient" (Score 3), in compliance with the Easy-to-Read guidelines. Instead, the other 3 captions reached an average level of "insufficiently correct" (Score 2). Based on the score achieved, the tool demonstrated a good structural foundation but presented some issues. For this reason, beyond the quantitative analysis, experts also provided qualitative input for each caption text, identifying its strong points and areas needing development. Among the main critical aspects, experts underlined limited exemplification, abstract phrasing, and inconsistent clarity, which prevented

[2] https://www.inclusion-europe.eu/

Table 2. Example of Easy-to-Read facilitation process: from the original text to the latest version prepared by the team after the review process.

Original text[1]	First version of the facilitated text made with ChatGPT 4[2]	Latest version of the facilitated text, produced through the co-design process[3]
Le aristocrazie picene usavano riunirsi in occasione di pasti comuni (banchetti o simposi). Si tratta di un'usanza tipica di molte civiltà antiche e la sua introduzione in area picena è legata ad un'influenza proveniente dal mondo greco, ben attestata anche tra gli Etruschi. Nei corredi delle tombe troviamo spesso oggetti riconducibili al banchetto, in particolar modo vasellame legato alla mescita del vino. Tra i vasi più rappresentativi troviamo: – crateri, grandi vasi per la preparazione del vino; – stamnoi e anforette, vasi di medio-grandi dimensioni utili alla conservazione dei liquidi; – piccole brocche (oinochoi); – recipienti di varia forma utilizzati per bere come le kilikes, larghe coppe su piede con due anse, e gli skyphoi, più piccoli e profondi.	Le persone importanti di un tempo lontano chiamato epoca picena si incontravano per mangiare insieme durante grandi feste. Questo costume era comune anche in altre culture antiche e ha raggiunto i Piceni grazie all'influenza dei Greci, proprio come era successo per gli Etruschi. Durante gli scavi delle tombe si trovano cose che venivano usate per queste feste, soprattutto per bere il vino. Tra queste cose ci sono grandi vasi per preparare il vino, altri vasi un po' più piccoli per tenerlo, piccole brocche e anche tazze di varie forme per bere.	Le famiglie più ricche e potenti del passato si chiamavano aristocratiche. Le famiglie aristocratiche si riunivano per fare pasti insieme. Questi pasti si chiamano banchetti o simposi. Nelle tombe troviamo spesso oggetti che si usavano nei banchetti per dimostrare che quella persona era importante. Tra questi oggetti troviamo dei vasi che venivano usati per miscelare il vino con l'acqua e alcune spezie e aromi.

[1] Authors' translation of the original text: "The Picenian aristocracies used to gather for common meals (banquets or symposia). This was a custom typical of many ancient civilisations and its introduction in the Picenian area is linked to an influence from the Greek world, also well attested among the Etruscans. In the grave goods of the tombs of Tolentino we often find objects that can be traced back to the banquet, especially vases related to the pouring of wine. Among the most representative vessels we find: craters, large vases for preparing wine; stamnoi and amphorae, medium-large vessels for storing liquids; small jugs (oinochoi); vessels of various shapes used for drinking such as kilikes, large bowls on feet with two handles, and skyphoi, smaller and deeper".

[2] Authors' translation of the first version of the facilitated text made with ChatGPT 4: "Important people from a distant time called the Picenian era met to eat together during great feasts. This custom was common in other ancient cultures as well, and it reached the Picenes through the influence of the Greeks, just as it had for the Etruscans. When excavating ancient tombs in a place called Tolentino, we often find things that were used for these feasts, especially for drinking wine. Among these things are large vessels for making wine, other somewhat smaller vessels for holding it, small jugs, and even cups of various shapes for drinking".

[3] Authors' translation of the final version of the text: "The richest and most powerful Picenian families were called aristocrats. Aristocratic families gathered to have meals together. These meals were called banquets or symposia. In the tombs of Tolentino we often find objects that were used at banquets to show that the person was important. Among these objects we find vases that were used to mix wine with water and some spices and aromas".

achieving full accessibility standards. In light of this evidence, texts were revised and refined through a co-design process involving teamwork, which allowed for direct user feedback and iterative adjustments. As a result, the revised captions achieved higher levels of compliance, with most texts receiving an average score between 4 and 5, indicating a strong alignment with the Easy-to-Read criteria. These improvements reflected the value of integrating technological tools with participatory methodologies to

enhance both linguistic clarity and cultural accessibility. Table 2 shows the reviewing process, from the original version to the latest one.

4. Discussion

This project suggests that AR and VR technologies can be effective in mitigating support needs related to the lack of predictability of museum spaces and content. Specifically, the use of VR can enable the anticipation of exploration of environments through the creation of immersive 360° maps, significantly reducing perceptions of anxiety and uncertainty associated with entering unfamiliar contexts (Campitiello et al., 2022; Drageset & Crippen, 2024). In parallel, AR can facilitate the integration of physical and digital reality by transforming information into accessible formats, such as converting verbal descriptions into visual or audio elements and vice versa (Hutson & Hutson, 2023, 2024). Due to their multisensory and multimodal nature, these technological solutions can enhance the visual channel, explicitly responding to the predominant cognitive styles of people with autism and significantly improving their experience of cultural enjoyment (Campitiello et al., 2022).

In the context of intellectual disability, particular attention has been devoted to the accessibility of written content through adopting the Easy-to-Read format, implemented by the competencies of people with intellectual disabilities (Floridi, 2022). To this end, it becomes essential to develop co-design strategies based on prompt engineering, whereby people with intellectual disability are actively involved in the formulation and validation of input prompts and textual outputs. Such participatory approaches not only improve the linguistic and cognitive accessibility of museum-related texts but also contribute to enhancing the agency and inclusion of people with disabilities as co-creators of cultural content. This dual investment in technological innovation and people empowerment represents a key direction for advancing accessibility within museum contexts (Shogren et al., 2022; Suárez-Figueroa et al., 2020).

This study highlights how the involvement of people with disability in co-design can help to develop and improve inclusive museum itineraries, creating multiple pathways to a virtuous synergy between museum cultural activities and social inclusion (Re & Valente, 2022). Collaboration with diverse professionals and people with disability emerges as a meaningful process that generates inclusive museum pathways and strengthens participants' personal and social empowerment (Guedes et al., 2023). In addition, this participatory approach allowed for the precise identification of the core functionalities and specific requirements of the digital solutions tested. Consistent with the principles of UD (Story et al., 1998) and with the relevant literature described in the Introduction, it is essential to promote synergy between technology and innovation to foster greater active involvement of all museum visitors (Carci et al., 2019; Solima, 2007).

5. Conclusions

This study underscores the necessity of developing accessible museum pathways, particularly focusing on people with autism and intellectual disability. Museums play a crucial role in cultural and educational dissemination, yet accessibility remains a significant challenge. By leveraging innovative technologies such as Virtual Reality, Augmented Reality, and Artificial Intelligence, museums can provide inclusive and engaging experiences that cater to a diverse audience. These technologies serve as essential tools for overcoming barriers that hinder the museum experience and for enhancing the interpretative and interactive aspects of cultural heritage engagement (Aliseda et al., 2023; Balcazar et al., 1998;

D'Angelo et al., 2024; Del Bianco et al., 2024; Giaconi et al., 2023; Olmedo-Pagés & Arquero-Avilés, 2024). Integrating co-design and innovative technologies, in line with the principles of Universal Design (Story et al., 1998), is a starting point for rethinking cultural contexts as spaces for inclusion, participation, and development.

However, while these advancements provide useful guidelines for significant transformations and valuable insights into museum accessibility, certain limitations require further analysis and suggest directions for future research.

Firstly, the specificity of the sample presents a significant constraint due to the small and limited number of people involved, as it focuses primarily on people with autism and intellectual disability. Future studies should expand their scope to include participants with different support needs, allowing for a more comprehensive and inclusive understanding of museum accessibility challenges and creating further pathways (Mesquita & Carneiro, 2016; Rappolt-Schlichtmann et al., 2013). In this regard, numerous paths can be taken in museum settings for people with disability through adaptation of contexts that could involve, for example, the use of simple procedural accouterments up to AI systems that adapt to people's needs in real time.

Moreover, although the present study concentrates on the application of Augmented Reality, Virtual Reality, and Artificial Intelligence within the context of museum accessibility, future research trajectories should encompass a broader spectrum of emerging technologies. Among these, haptic feedback systems, brain-computer interfaces (BCIs), and multisensory immersive environments represent particularly promising avenues for investigation. Such technologies may not only function as complementary tools but also provide alternative modes of access to cultural heritage, thereby contributing to the construction of diversified and multimodal interpretative ecosystems (Diamantopoulou et al., 2024). In particular, the affordances generated by these innovations may be especially relevant for people with complex or multiple disabilities, offering unprecedented opportunities for interaction, engagement, and cognitive-emotional involvement with museum content.

Concomitantly, the implementation of inclusive digital strategies is not solely contingent upon the availability of technological infrastructure but critically hinges on the competences, attitudes, and preparedness of museum personnel. It is, therefore, important that forthcoming research initiatives incorporate the design, empirical validation, and systemic dissemination of professional development programs aimed at museum staff. These training initiatives should be multidimensional in scope, encompassing both technical skills pertaining to the operation and contextual adaptation of assistive technologies, as well as relational competences, including inclusive communication strategies (Klavina et al., 2024). Only through the integration of technological innovation with personalized approaches can the goal of systemic accessibility in cultural institutions be meaningfully pursued.

Based on this evidence, this study aimed to highlight the crucial importance of adopting a systemic and collaborative approach that involves experts, institutions, and people with disability at every stage of design to promote a genuinely participatory and inclusive culture. Through the synergistic integration of technological innovation, inclusive design, and co-design, museum settings can increase their educational and cultural role and strengthen their social function as places of inclusion, participation, and sharing of cultural heritage.

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From analysis to practice: The creation of podcasts in special education teacher training

Dall'analisi alla pratica: La creazione di podcast nella formazione dei docenti di sostegno

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Abstract The use of digital technologies in teacher training represents a strategic lever for teaching innovation, especially in the field of educational support. In this context, educational podcasts emerge as effective tools to foster school inclusion and support personalized learning. The present study analyzed the process of selection, evaluation and use of applications for the creation of podcasts, as well as their impact on the training of future special needs teachers. The research was conducted as part of the Support Qualification Course of the University of Palermo, involving 96 students divided between lower and upper secondary schools. During two practical sessions of five hours each, students explored and tested a selection of podcast creation applications, previously evaluated through the Mobile Application Rating Scale (MARS) by three independent evaluators. The results of the MARS evaluation highlighted the best performing applications, thanks to their intuitiveness, stability and quality of audio output.

KEYWORDS Podcast; Inclusive Teaching; Digital Technologies; Teacher Training; Mobile Application Rating Scale (MARS).

Sommario L'uso delle tecnologie digitali nella formazione dei docenti rappresenta una leva strategica per l'innovazione della didattica, specialmente nell'ambito del sostegno educativo. In questo contesto, i podcast educativi emergono come strumenti efficaci per favorire l'inclusione scolastica e supportare l'apprendimento personalizzato. Il presente studio ha analizzato il processo di selezione, valutazione e utilizzo di applicazioni per la creazione di podcast, nonché il loro impatto sulla formazione dei futuri docenti di sostegno. La ricerca è stata condotta nell'ambito del Corso di Abilitazione Sostegno dell'Università degli Studi di Palermo, coinvolgendo 96 corsisti suddivisi tra scuola secondaria di primo e secondo grado. Durante due sessioni di cinque ore ciascuna, gli studenti hanno esplorato e testato una selezione di applicazioni per la creazione di podcast, precedentemente valutate attraverso la Mobile Application Rating Scale (MARS) da tre valutatori indipendenti. I risultati della valutazione MARS hanno evidenziato le applicazioni più performanti, grazie alla loro intuitività, stabilità e qualità dell'output audio.

Parole chiave Podcast; Didattica Inclusiva; Tecnologie Digitali; Formazione Docenti; Mobile Application Rating Scale (MARS).

1. Introduction

The use of podcasts in teaching is a topic of growing interest both nationally and internationally, as they represent a versatile tool capable of improving educational practices and expanding learning opportunities.

In this framework, this contribution is part of the contemporary debate on extended education, understood as the expansion of places, times and methods of learning outside the traditional bounda-

ries of the classroom. Extended education promotes the idea of widespread, accessible and constructed knowledge even in informal and unstructured contexts, in line with a dynamic and inclusive conception of the educational process. In this sense, podcasting represents a practice that is highly consistent with this vision, as it allows students to learn autonomously and flexibly, enjoying educational content at times and environments different from conventional school environments. In addition, in teacher training, the podcast is configured as a tool capable of stimulating pedagogical reflection, shared planning and the activation of professional skills through production and co-creation activities. The experience described here, carried out as part of the Support Qualification Course, aims to enhance these dimensions, placing podcasting at the center of a training approach that fully embodies the principles of extended education.

While the integration of digital technologies into the training process offers numerous benefits, such as the possibility of facilitating the exchange of ideas and creating more engaging educational content, challenges persist related to their practical implementation and pedagogical aspects.

The integration of digital tools into teaching can improve learning, fostering greater interaction and active involvement of students, as Mayer (2009) points out. In particular, podcasting has established itself as an effective methodology to support collaborative learning and communication between students, promoting a more dynamic and critical approach (González Enríquez & Cutuli, 2023).

Starting from these theoretical premises, the present research has focused on two main objectives. First, an analysis of podcast creation applications was conducted, with the aim of identifying those most suitable for educational use. For this assessment, the Mobile Application Rating Scale (MARS) (Stoyanov et al., 2015) was adopted, a tool that allows to measure the quality and usability of digital applications in the educational field. Three independent researchers, experts in educational technologies, analyzed a selection of apps, evaluating them based on criteria of intuitiveness, stability and quality of audio output, in order to identify the most effective solutions to support the production of educational content.

The second objective of the research concerned the practical application of podcasting in the training of support teachers. The survey was conducted in the Support Qualification Course of the University of Palermo, involving 96 students belonging to lower and upper secondary schools. The students, divided into groups, made educational podcasts addressing topics covered in the course. At the end of the course, a questionnaire was administered (Hanson et al., 2023) to collect the participants' perceptions of the effectiveness of podcasting as a learning tool, assessing their level of involvement, satisfaction and any difficulties encountered in the production process.

The analysis of the data collected has shown how podcasting can represent an innovative and stimulating teaching methodology, capable of improving interaction between students and promoting more active and participatory learning. However, the research also highlighted some critical issues, in particular related to technical difficulties in the use of applications and the management of group work. These results suggest the need for greater structuring of the training pathway, so that podcasting can be integrated more effectively into educational contexts.

The results obtained offer important food for thought for the design of educational paths that exploit the potential of podcasting, helping to make learning more inclusive, dynamic and personalized.

2. From digital technologies to educational innovation: The podcast as a tool for transformation

In recent years, digital technologies have profoundly transformed the education sector, introducing innovative approaches to teaching and learning. The integration of educational technologies goes

beyond the mere digitization of materials, fostering interactive, flexible, and accessible learning environments that enhance student engagement and improve educational quality (Clark-Wilson et al., 2020; Mayer, 2009). The adoption of digital tools in childhood and adolescence is progressively redefining the ways in which knowledge is acquired, influencing the entire education system (Clark-Wilson et al., 2020; Colella, 2016).

Among digital resources, educational podcasts are increasingly recognized as innovative tools that promote flexible and student-centered learning approaches. In particular, student-generated podcasts have been shown to enhance subject understanding, peer connection, and academic performance, fostering active learning and knowledge construction (Hernandez-Lopez & Mendoza-Jimenez, 2025).

The use of podcasts in teacher training has been widely investigated, with studies demonstrating their effectiveness in enhancing student engagement and supporting deeper content understanding (Heilesen, 2010). The asynchronous nature of podcasts allows students and teachers to enjoy content in a personalized way, adapting the learning times and rhythms to their needs. In addition, the ability to create and share podcasts gives students a more active role in the learning process, transforming them from mere users to producers of educational content (Hyangsewu, 2024).

Psychological constructivism conceives learning as a dynamic process centered on knowledge construction rather than passive transmission (Vygotsky, 1978), a perspective that continues to inform contemporary digital learning environments (Clark-Wilson et al., 2020).

The use of podcasts in teaching is significant in fact, as it goes beyond the mere transmission of audio content, transforming itself into a means to actively engage students, stimulate critical thinking and promote the personalization of learning. For example, the creation of podcasts by students not only favors the acquisition of technical skills, but leads to a substantial change in their participation in the educational process, making them protagonists of the construction of knowledge.

This approach reflects the idea that technology, like podcasts, must be integrated in a conscious and targeted way, so that it produces profound changes in educational practices and is not limited to superficial adoption. Thus, a school that uses podcasts in an authentically innovative way does not limit itself to "certifying" the presence of technological tools, but integrates them to truly transform the learning experience, stimulating creativity, collaboration and critical thinking.

The use of podcasts in teaching is a topic of growing interest both nationally and internationally. According to Besser et al. (2022), podcasting is taking on an increasingly relevant role in higher education, providing students with more flexible and immersive learning opportunities. In addition, its use is spreading in different educational contexts, promoting greater involvement and improving the quality of teaching.

Despite the benefits of integrating digital technologies into the educational process, such as facilitating the exchange of ideas and creating innovative content, several challenges remain related to their practical implementation and pedagogical aspects. These include technical and accessibility difficulties (Newman et al., 2021), the need for training for teachers (Cecilio-Fernandes et al., 2020), and the challenge of effectively integrating them with traditional methods (Kelly et al., 2022).

Gunderson and Cumming (2023) highlight how podcasting can be integrated into Universal Design for Learning (UDL) to promote more inclusive education, adapting to the diverse needs of students and improving accessibility to learning content.

To address these challenges, the use of podcasts as a teaching tool aims to foster more participatory, dynamic and conscious learning, improving students' critical understanding and communication skills. Moore (2024) points out how podcasting can also be used effectively in specific academic dis-

ciplines, such as planning and social sciences, demonstrating its potential to enrich the educational experience in the university setting.

Inclusive education requires the adoption of strategies and tools that make it possible to respond to the needs of students with Special Educational Needs (SEN), providing accessible and customizable materials. According to Oforji and Whitnall (2025), podcasts are particularly effective tools for school inclusion as they allow you to overcome the traditional barriers of face-to-face teaching, offering learning methods that are more adaptable to individual needs.

Several studies have shown that podcasts can improve participation and understanding of content by students with learning difficulties, allowing them to listen to the materials again, take advantage of auditory support and facilitate understanding through the use of clear and structured language. According to Abubakar et al. (2025), podcasting can enhance teaching effectiveness by allowing students to review content multiple times and adapt the pace of learning to their needs. Similarly, Indahsari (2020) highlights that podcasts can offer up-to-date content and authentic native voices, improving learning comprehension and accessibility. In addition, several studies have highlighted how podcasting can strengthen listening and comprehension skills, supporting more effective knowledge acquisition (Besser et al., 2022; Gunderson & Cumming, 2023).

The ability to create multimedia content also helps students with specific learning disabilities (SLD) or special educational needs to express their skills in alternative ways that are better suited to their abilities (Sulaeman et al., 2025).

The use of podcasts in inclusive contexts has been increasingly integrated into teacher education programs, particularly when aligned with Universal Design for Learning principles, as it supports flexible access to content and reflective pedagogical practice (Gunderson & Cumming, 2023).

However, it is important to note that podcasting, as an audio format, presents critical issues in terms of accessibility for students with hearing disabilities. To ensure that this tool can truly support inclusive education, it is necessary to provide forms of compensation, such as transcribing content, inserting subtitles or supporting supplementary visual materials. The adoption of these strategies makes it possible to extend the benefits of podcasting to a wider audience, ensuring equal access to learning even in the presence of sensory disabilities.

3. Research methodology

The present study aims to analyze the impact of the use of podcasting in the training of future support teachers, evaluating both its effectiveness in the creation of educational content and the perception of students with respect to this methodology. The research aims to provide a detailed picture of the potential of podcasting in inclusive teaching, examining the most suitable applications for the production of educational content, the degree of involvement of students in podcast creation activities and the perceived effectiveness of this tool in teaching.

The selected sample is non-probabilistic, consisting of 96 students enrolled in the Specialization Course for Support Activities (IX cycle) at the University of Palermo. This sampling methodology was adopted by virtue of the availability and accessibility of the participants, while acknowledging the limitations in terms of generalizability of the results.

A first objective of this research is to identify and evaluate the applications for the creation of podcasts most suitable for educational use, with particular reference to the context of teacher training. To ensure a methodologically rigorous selection, the applications were analyzed by three independent

researchers, experts in educational technologies, through the Mobile Application Rating Scale (MARS), a widely used tool to assess the quality of digital applications in education. The MARS analysis made it possible to identify the apps with the best characteristics in terms of accessibility, ease of use, quality of information provided and educational impact, thus allowing the selection of the most suitable ones for the production of educational podcasts.

A second objective is to examine the impact of podcasting as a practical activity in the training of support teachers. The students participating in the research worked in groups to create an educational podcast, lasting 8-10 minutes, using the selected applications. The activity made it possible to explore the ways in which podcasting can stimulate creativity, collaborative work and active involvement in the construction of knowledge. In addition, the design and implementation of audio content aimed at teaching students with Special Educational Needs (SEN) has made it possible to reflect on the potential of this tool with a view to school inclusion.

At the same time, a further objective of the study concerns the analysis of students' perception of the use of podcasting in teaching and its usefulness in the training of support teachers. To collect data on this, a structured questionnaire was administered, based on an instrument validated in previous research (Hanson et al., 2023). The questionnaire included 20 multiple-choice questions and three open-ended questions, aimed at collecting information on the ease of use of the applications, the level of involvement in the activity and the perceived usefulness of podcasts for inclusive teaching. The analysis of the answers will allow to better understand the role of podcasts in teacher training and to identify any critical issues in the use of this tool in training contexts.

Finally, the research aims to develop practical guidelines for the integration of podcasting into inclusive teaching, offering indications for the effective use of this technology in the training of special needs teachers. Through the analysis of the results obtained from the MARS evaluation and the questionnaire, it will be possible to define strategies to optimize the use of podcasts in teaching and suggest ways to integrate the production of audio content into teachers' training paths.

3.1. Search and selection criteria for podcast applications

Before proceeding with the evaluation of applications with the Mobile Application Rating Scale (MARS), it was necessary to identify and select the most suitable tools for creating podcasts in the educational field. To identify the best free solutions for creating podcasts, a preliminary analysis was conducted that involved not only the mobile applications available on digital stores, but also web platforms that allow the recording, editing and publication of podcasts without the need to download a dedicated application.

Research included:

1) Google Play Store (for Android devices)
2) Apple App Store (for iOS devices)
3) Free web platforms accessible via browser, selected for their ease of use and available features.

To get a wide and up-to-date selection, several key search terms were used:

1) "Podcast Editor"
2) "Podcast Recording"
3) "Create Podcast"
4) "Podcast App for Beginners"
5) "Free Online Podcast Maker"

The analysis produced a total of 896 apps on the Google Play Store and 854 apps on the Apple App Store. In addition, 15 web platforms have been identified that offer free tools for creating and editing podcasts.

To ensure that only the most suitable applications and platforms were included in the evaluation phase, the following exclusion criteria were applied:

Table 1. List of Exclusion Criteria.

Exclusion Criteria	Description
Lack of compatibility	Excludes apps that are only available for one operating system (iOS only or Android only). Keep only cross-platform or browser-accessed apps.
High costs	Excludes apps with mandatory subscription. Only free or freemium apps with essential functions are kept in the free version.
Not enough reviews	Excludes apps with less than 100 total reviews, as they are poorly tested by users.
Low review score	Excludes apps with less than 3.5 out of 5 stars. Only those with a minimum of 4.0 stars are maintained.
Incomplete features	This excludes apps that did not offer at least three essential features (recording, editing, exporting). Keep only those with advanced editing tools.
Access restrictions	Spotify for Podcasters excluded due to the need for Spotify accounts. We only include platforms that allow the creation of podcasts without the obligation to register.
Language not accessible	Excludes apps that are only available in English without an intuitive interface. Keep only those with support in English or simple interface.
Obsolescence	Excludes apps that haven't been updated for more than two years. Only those updated from 2023 onwards have been maintained.

After applying the selection criteria, the total number of applications and web platforms has been reduced to 12 solutions, which will be evaluated with the Mobile Application Rating Scale (MARS) to identify those most suitable for educational use in the context of the training of support teachers.

The research update has made it possible to include not only mobile apps, but also online platforms that offer advanced tools for creating podcasts without the need to download specific software.

While the exclusion criteria applied ensured the selection of applications that were stable, accessible, and supported by a sufficient degree of user validation, a potential limitation remains. Emerging or niche solutions, although potentially valuable for educational use, may have been excluded due to a limited number of reviews, recent updates, or still limited uptake.

Although this approach increased the reliability of the selection process, it may affect the generalizability of the results, as the apps analyzed represent only a fraction of the rapidly evolving landscape of educational podcasting tools.

3.2. Mobile Application Rating Scale (MARS)

The evaluation of the selected applications and web platforms was conducted using the Mobile Application Rating Scale (MARS), a standardized tool designed to provide a reliable and reproducible assessment of the quality of mobile applications.

The MARS is a multidimensional rating scale, developed to measure the quality of mobile applications, initially in healthcare (Stoyanov et al., 2015) and later adapted to educational contexts. MARS enables structured and reproducible evaluation of applications,

Table 2. List of selected applications and platforms.

Name	Type	Platform	Accessibility	Main functions
Soundtrap	Web-based (browser)	Online	Free	Recording, editing, publishing
Anchor (ex Spotify for Podcasters)	App	iOS/Android	Free with restrictions	Registration and publication
Podbean	App/Web-based	iOS/Android/Online	Free	Recording, editing, hosting
Spreaker Studio	App/Web-based	iOS/Android/Online	Free	Recording, sound effects, live streaming
Dolby On	App	iOS/Android	Free	High-quality audio recording
Easy Voice Recorder	App	iOS/Android	Free	Basic recording and simple editing features
GarageBand	App	iOS/MacOS	Free	Recording, advanced music editing
Audacity (Web version)	Web-based (browser)	Online	Free	Advanced audio editing and multitrack capabilities
Zencastr	Web-based (browser)	Online	Free	Audio/video recording for interviews
Hindenburg Journalist	App/Web-based	iOS/Android/Online	Free	Advanced editing for professional podcasts
Riverside.fm	Web-based (browser)	Online	Free	High-quality recording, automatic editing
Castbox Creator Studio	App/Web-based	iOS/Android/Online	Free	Recording, distribution podcasts

Table 3. Structure of the Mobile Application Rating Scale (MARS).

Category	Description
Engagement	Is the app inspiring and engaging for users? Does it have interactive or customizable elements?
Functionality	Is the app stable and bug-free? Is navigation intuitive and smooth?
Aesthetics	Does the app have a clear and visually appealing layout? Is the design consistent and professional?
Information Quality	Is the information provided accurate, reliable and well-structured? Are there tutorials or learning materials?
Subjective Quality	How useful and enjoyable do users find the app? Would they recommend the app to other users?

The MARS scale consists of 5 main categories, each with sub-dimensions rated using a 5-point Likert scale (1 = Very Bad, 5 = Excellent) (Table 3).

Each application receives an overall MARS score derived from the average of the ratings assigned in each category.

3.2.1. Evaluation methodology

The evaluation was conducted by three independent researchers, experts in educational technologies, selected to ensure consistency and reliability in the application of the MARS scale.

Before performing the assessments, the assessors were provided with specific training on the MARS scale, in order to ensure a thorough understanding of the evaluation criteria and a consistent application of the tool. This step ensured greater inter-rater reliability between evaluators.

1) Each evaluator downloaded and installed the 12 selected applications and platforms. The Evaluators tested each app and site following a standardized protocol:
   - Recording a short audio
   - Editing and applying effects
   - File export
   - Interaction with any advanced features
2) After testing each app, the evaluators filled out the MARS card, assigning a score from 1 to 5 for each category.
3) The scores were aggregated and analyzed to obtain the final average score for each app.

3.2.2. Results of the MARS assessment

To collect data in a structured way, each evaluator compiled a MARS evaluation grid for each application tested.

Table 4 shows the average score obtained from the three evaluations for each application, ensuring a reliable indication of the overall quality of the selected apps.

For the purposes of the practical activity planned with the trainees, the five applications with the highest average MARS score were selected: GarageBand, Soundtrap, Dolby On, Audacity Web and Riverside.fm. The choice was based on two criteria: the achievement of an average score equal to or greater than 4.45, corresponding to an "excellent" or "very good" quality level according to the MARS score interpretation criteria reported in Table 5; the free or freemium availability of the applications, in order to ensure accessibility to all participants.

This targeted selection had a concrete impact on the laboratory phase of the intervention: the trainees, divided into groups, were able to choose from the five recommended applications based on their preferences and technical skills. The use of tools already validated in the preliminary phase facilitated collaborative work, reduced technical difficulties and improved the quality of the final products, as also noted in the subsequent subjective evaluation. In addition, the possibility of comparing different user experiences has contributed to increasing critical awareness with respect to the digital tools available for teaching.

Table 4. Average scores assigned according to the MARS instrument.

Application/Platform	Engagement	Functionality	Aesthetics	Information Quality	Average MARS score
Soundtrap	4.5	4.7	4.6	4.8	4.65
Podbean	4.2	4.3	4.5	4.7	4.43
Spreaker Studio	4.0	4.2	4.3	4.5	4.25
Dolby On	4.3	4.6	4.8	4.2	4.47
GarageBand	4.6	4.9	4.7	4.6	4.7
Audacity (Web)	4.2	4.8	4.4	4.5	4.47
Zencastr	4.1	4.5	4.3	4.6	4.38
Hindenburg Journalist	4.0	4.7	4.5	4.7	4.48
Riverside.fm	4.3	4.5	4.6	4.5	4.48
Castbox Creator Studio	4.2	4.4	4.3	4.6	4.38
Easy Voice Recorder	3.9	4.0	4.2	4.3	4.1
Anchor (ex Spotify for Podcasters)	3.8	4.1	4.0	4.2	4.03

Table 5. Criteria for interpreting MARS scores.

Average MARS score	Application quality level
4.5 - 5.0	Excellent – Highly recommended application for educational and didactic use.
4.0 - 4.4	Good – Recommended application with some minor limitations.
3.5 - 3.9	Acceptable – Application with some shortcomings that can limit the user experience.
3.0 - 3.4	Mediocre – Application with several limitations, recommended only in specific cases.
< 3.0	Not recommended – Application with significant issues that make it difficult to use for education.

3.2.3. Analysis of the results

An analysis of the scores shows that GarageBand (4.7), Soundtrap (4.65), and Dolby On (4.47) are the three highest-rated platforms, thanks to their combination of high-quality audio output, advanced features, and an intuitive interface.

- GarageBand scored the highest in functionality and aesthetics, standing out for its professional interface and extensive editing options.
- Soundtrap was particularly suitable for collaborative teaching, thanks to the ability to work on shared tracks in real time.
- Dolby On was rated positively for its audio quality and ease of use, making it a great choice for users with no experience in podcast production.

On the other hand, platforms like Anchor (4.03) and Easy Voice Recorder (4.1) scored lower and fall into the "Good" category, as they have some limitations:

- Less advanced editing than top-rated applications.
- Fewer customization options for creating learning content.
- Limited features in the free version.

As mentioned in the previous paragraph, only the applications with the highest MARS scores were used in the lab phase, ensuring consistency between the initial assessment and the actual user experience. This choice allowed the trainees to work with reliable and qualitatively validated tools, promoting more effective learning and active involvement in the podcast creation process.

3.3. Practical activity: creation of podcasts by the trainees

After the selection and evaluation of applications with the Mobile Application Rating Scale (MARS), the trainees participated in a practical activity aimed at directly experiencing the process of creating and using podcasts in the educational field.

The activity was conducted within the Specialization Course for Support Activities (IX cycle) of the University of Palermo, involving 96 students, divided between lower secondary school (58 participants) and upper secondary school (38 participants).

The activity has been designed with a dual purpose:

- To encourage an active deepening of one of the topics studied during the course.
- Create an archive of audio content to be used to review the other topics covered by the other groups, in view of the final exam.

The activity was developed through a path structured in two sessions lasting five hours each (for a total of ten hours), during which the trainees worked in groups to design and create an educational podcast. The process was divided into several phases, with the aim of allowing active and

collaborative learning, using podcasting both as a tool for in-depth study and consolidation of the knowledge acquired.

In the initial phase, the trainees were introduced to the use of the selected applications through the MARS scale, with an analysis of their functionalities and the differences between the platforms. After this initial familiarization phase, each group chose the app that best suited their needs, based on the characteristics evaluated and the preferences of the participants.

Subsequently, in the design and in-depth phase, the students were divided into groups of five to seven participants. Each group was assigned a topic studied during the course, which had to be developed and deepened through the creation of the podcast. The activity had a dual purpose: on the one hand, to allow the students to study and rework their topic in a communicative key, and on the other, to encourage collective revision by listening to the podcasts made by the other groups, in view of the final exam. In this phase, the podcast outline was also defined, structuring the content, assigning the narrative voices and organizing the speech to ensure a clear and coherent flow.

The recording and editing phase represented the practical moment of the activity, during which the students used the apps to record the podcast, improve the quality of the audio through editing tools and possibly insert sound effects to make the final product more effective. Once the processing process was complete, the podcasts were exported and shared with the other groups.

Listening and collective review constituted a further moment of learning: each group presented their podcast to the class, while the other trainees had the opportunity to listen and take notes on the topics covered. This has fostered an active discussion, allowing a comparison on the contents that emerged and strengthening understanding through the sharing of knowledge.

Finally, the evaluation of the activity was conducted through a structured questionnaire adapted from Hanson et al. (2023) to investigate trainees' experiences and their level of satisfaction with the use of podcasting as a teaching tool. The questionnaire made it possible to collect data on students' perceptions of the effectiveness of podcasting in their learning process, highlighting strengths and possible critical points.

This experience has shown how podcasting can be not only an innovative teaching method, but also an effective tool to promote collaboration, autonomous content reworking and shared revision, offering students an active and engaging learning experience.

3.3.1. Data analysis

The analysis of the data collected in the questionnaire was conducted through a descriptive quantitative approach, with the aim of examining the perceptions and experiences of the trainees relating to the use of podcasts in teaching. The survey was structured according to a non-experimental and transversal methodology, based on numerical data collected in a single moment in time.

The quantitative analysis was developed through descriptive statistics, which made it possible to summarize and present the data clearly and effectively. For each variable investigated, absolute and relative frequencies were calculated, and the results were represented by bar and pie charts, facilitating the interpretation of the trends that emerged.

The use of the 5-point Likert scale made it possible to assess the degree of agreement or perception of the participants on key aspects of the survey, such as the perceived effectiveness of podcasts for review, their usefulness compared to reading texts and the impact on collaboration in group work. However, this approach provides a detailed picture of participants' opinions and experiences, which is

useful for identifying significant trends and patterns in the context of podcast-supported teaching.

The questionnaire administered to the students was taken from the research by Hanson et al. (2023), entitled "Examining University Student Podcasts and Evaluating Apps Using the Mobile App Rating Scale (MARS)", and translated into Italian by two experts independently in order to ensure semantic and cultural adherence to the reference context.

The questionnaire, administered to 96 students of the Support Qualification Course of the University of Palermo, consisted of 20 multiple-choice questions and 3 open questions.

The main sections investigated included:

- General perception of the activity (engagement and involvement);
- Usefulness of podcasting for revision (ease of access, storage of content);
- Learning preferences (podcasts vs. traditional methods);
- User experience of the selected applications (functionality, stability, ease of use).

The questionnaire was administered online, at the end of the activity with a moment dedicated to compilation, in order to ensure wide participation and collect representative data on the experience of the trainees.

Importantly, the data collected is self-reported in nature and reflects the subjective perceptions of participants. While this type of data offers useful information on the degree of involvement and individual preferences, it does not allow us to objectively measure the real effects of the activity on performance or on the acquisition of skills. In the future, the integration of quantitative assessment tools (such as pre- and post-activity tests or benchmarking) could strengthen the analysis of the educational impact of podcasting.

The sample was mainly composed of women (65 participants, equal to 68%), while there were 30 males (31%) and 1 trainee preferred not to specify gender (1%) (Figure 1).

The mean age of the participants was 37.8 years, with a range of 25 to 62 years. The most represented group was between 30 and 45 years old, in line with the typical age of the trainees of the specialization courses for support (Figure 2).

Subsequently, a survey was conducted to explore the level of awareness of students regarding the use of podcasts in education. To the question "Before this experience, did you know that podcasts could be used in teaching?" (Figure 3), the responses highlighted the following distribution:

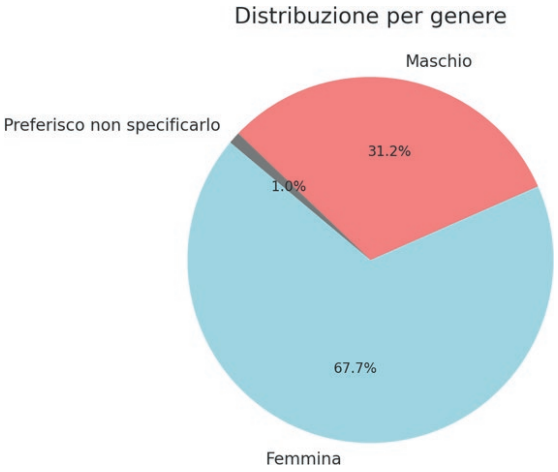

Figure 1. Distribution by gender.

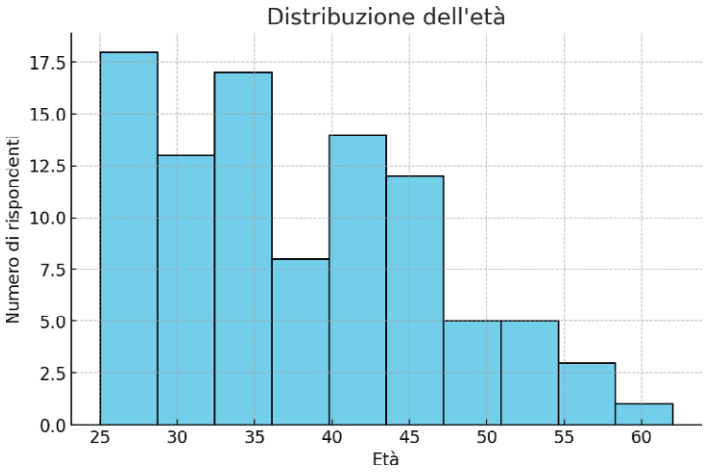

Figure 2. Age distribution.

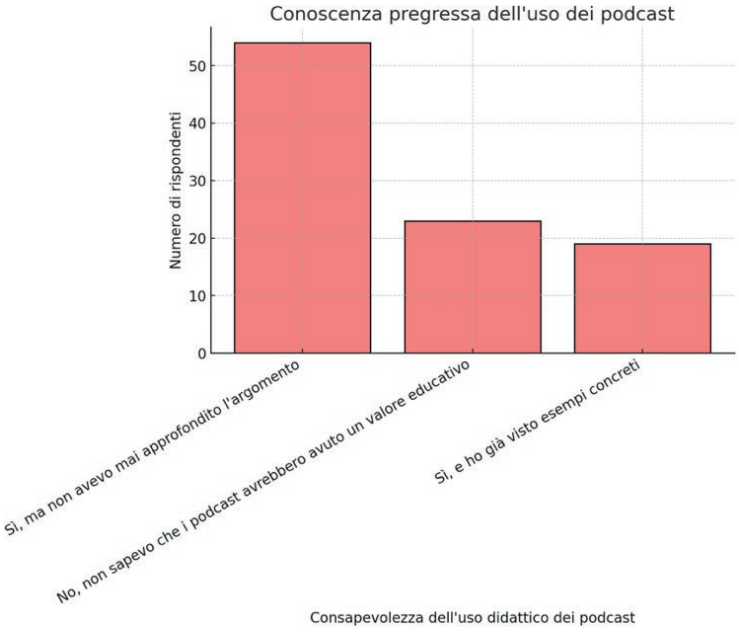

Figure 3. Awareness of the educational use of podcasts.

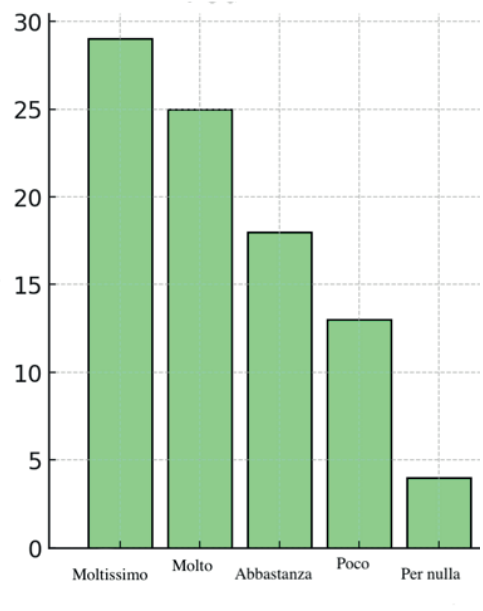

Figure 4. Podcast Vs. Learning text.

– 56% of the trainees knew about the didactic use of podcasts but had never delved into the topic.
– 24% of the trainees were unaware of their educational value.
– 20% of the students had already seen concrete examples of the didactic application of podcasts.

One of the objectives of the questionnaire was to compare podcasting with traditional methods of study, in particular reading texts (Figure 4). The responses collected outlined the following picture
– 30% of the students said they prefer podcasts "a lot" over written texts.
– 26% of students rated the usefulness of podcasts as "enough".
– 19% of the students indicated a low preference for audio over text.
– 14% of the students rated the podcast as "Very useful" compared to the written text.
– 4% of the trainees said they do not find learning through podcasts useful.

This data suggests that while the majority of students find podcasting useful, there is a significant portion that continues to prefer written texts, highlighting the need for blended approaches that combine multiple learning modalities.

A central aspect of the survey was to assess whether the podcast had been an effective method for reviewing and memorizing course content (Figure 5). The replies revealed the following breakdown:
– 35% of the students considered that the podcast was "quite" useful for revision.
– 30% of the trainees expressed a "very" positive opinion.
– 26% of the students rated the podcast as "very" useful.
– 2% of the trainees selected "Not at all", indicating that the podcast was not useful for revision.
– 5% of the students chose "Poco", considering it useful to a limited extent.

These results confirm that podcasting was perceived as a valuable tool for reviewing course content, improving understanding and consolidation of information.

The use of podcasting was also evaluated in terms of collaboration between trainees, given that the creation of audio content requires coordination and sharing of tasks (Figure 6). The answers reported the following breakdown:

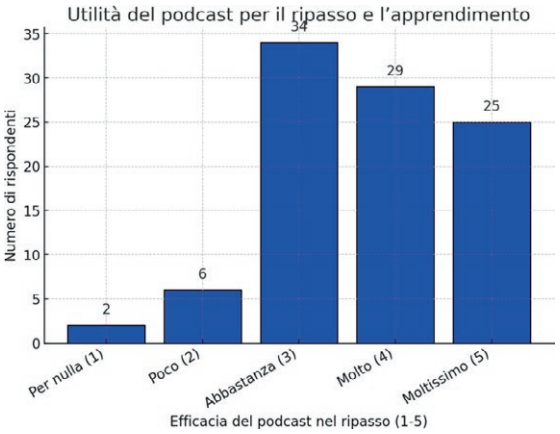

Figure 5. Effectiveness of Podcasts in revision.

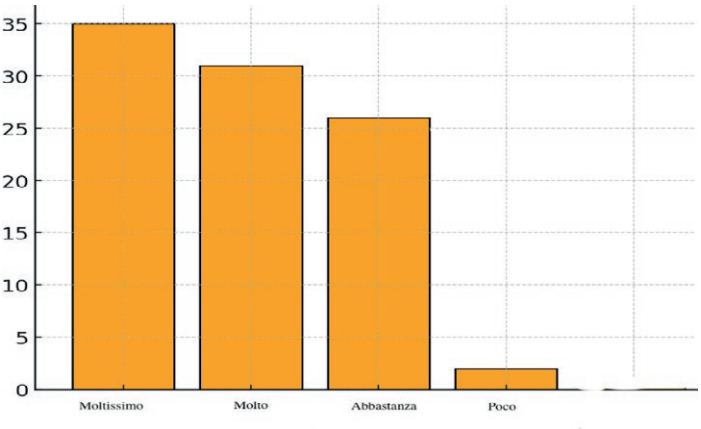

Figure 6. Impact of podcast on collaboration.

- 36% of respondents said podcasting had "very" favored collaborative work.
- 32% of the trainees found it "quite useful" for collaboration.
- 27% of the trainees evaluated the activity positively, but with less enthusiasm.
- 2% of the trainees felt that the activity had no positive impact on collaboration.

These data suggest that the creation of podcasts can be an effective educational activity to encourage collaborative work, albeit with some critical issues related to the organization of group work.

The analysis of the questionnaire confirms that the experience of creating and using the podcasts had a positive impact on the learning of the trainees.

In particular, podcasting was considered a valid tool for revision, helping to improve the understanding of the contents covered. The data collected also shows that 56% of participants were already aware of the educational use of podcasts, although only 20% had had direct experience of using them in an educational setting.

As for the comparison with traditional study methods, 30% of students said they found the podcast more effective than reading written texts, while 26% considered it "somewhat" useful. Finally, the use of podcasting encouraged collaboration in group work, facilitating the active involvement of students and promoting greater interaction between trainees.

However, some trainees reported technical and coordination difficulties, suggesting the need for a more structured guide for the creation and management of podcasts in the educational field.

The integration of podcasting into university teaching represents an opportunity to foster more inclusive and personalized learning, but its success depends on the availability of adequate tools and the training of teachers on the use of digital technologies.

4. Limitations of the study and prospects for improvement

Despite the positive results that emerged from the analysis, the use of podcasts in university teaching presents some critical issues that must be considered for a more effective and conscious integration within training practices. One of the main limitations concerns the technical difficulties encountered by some trainees in the process of creating and managing podcasts. The lack of familiarity with audio editing tools and recording platforms represented an obstacle for some of the students, highlighting the need for a more structured training on the use of digital technologies. To overcome this difficulty,

it would be advisable to introduce specific training moments before the start of the activity, providing practical tutorials and selecting intuitive and accessible tools that facilitate the creative process.

Another critical aspect that emerged concerns the differentiation in learning preferences. While many students appreciated the podcast as a tool for revision and in-depth study, some students continued to prefer traditional reading, considering it more effective for their learning style. This suggests that podcasting, while a valuable educational tool, cannot be considered a universal solution for all students. For this reason, it would be useful to adopt a multimodal teaching approach, in which the podcast is accompanied by written and visual materials, allowing students to choose the format that best suits their needs.

A further limitation encountered concerns the management of group work. Although the creation of the podcast has fostered collaboration among the trainees, some have reported, through the questionnaire administered at the end of the course, difficulties in organizing work and dividing tasks. The indications provided at the beginning of the activity left the groups a wide margin of organizational autonomy: each group was in fact invited to structure itself freely, distributing tasks on the basis of the skills, individual propensities and strengths of the individual participants. This approach, aimed at stimulating self-management and empowerment, has however highlighted some critical issues, especially in groups less accustomed to collaborative work. Some trainees reported moments of uncertainty in the definition of roles and in the management of timing. In view of future implementations of the activity, it would be appropriate to combine this initial flexibility with more detailed operational guidelines, which offer examples of possible roles (such as coordinator, content manager, audio technician, reviewer) and a clear sequence of work phases (brainstorming, drafting, recording, editing). The use of shared digital tools (such as Google Docs) could also facilitate the planning and monitoring of the process. Such measures would make it possible to better support the groups, while maintaining organizational freedom.

Finally, a methodologically relevant and potentially limiting aspect concerns the evaluation of the effectiveness of podcasting on learning. The analysis conducted was based exclusively on self-reported data, obtained through a questionnaire administered to the trainees at the end of the activity. While this approach has made it possible to gather useful information about individual perceptions, it does not allow us to accurately determine the actual impact of podcasting on skills development or learning outcomes. This absence of objective measurement represents an important criticality, which reduces the robustness of the results and limits their generalizability. To strengthen the validity of the data, future studies should integrate more rigorous assessment methods, such as pre- and post-activity learning tests, comparisons with control groups, or analyses of academic achievements. These tools would make it possible to evaluate the effectiveness of podcasting more accurately, going beyond the perceived dimension alone and offering more solid evidence to support the integration of these tools into university teaching.

In conclusion, while showing promising results, the integration of podcasting into teaching needs further improvements to overcome technical difficulties, adapt to different learning preferences, optimize the management of group work and deepen the evaluation of its actual impact. In particular, it seems a priority to combine teaching support tools with more solid evaluation methodologies, capable of objectively detecting the benefits of the training activity. The introduction of more flexible teaching strategies, multimodal supplementary materials and standardized measurement tools could facilitate the adoption of podcasting as an innovative, reflective and inclusive learning method.

5. Conclusions

The analysis conducted highlighted the educational potential of podcasting in university teaching, highlighting how this tool can promote revision, knowledge consolidation and collaborative work among students. The results obtained confirm that the creation and listening to podcasts represented a stimulating and useful activity for the trainees for learning, with a good part of them evaluating the experience positively. However, the study also highlighted some critical issues that require careful reflection to improve the effectiveness of this methodology.

A central aspect that emerged from the survey concerns the perceived effectiveness of the podcast for revision and learning. The majority of the students felt that this activity improved their understanding of the contents covered in the course, offering a more dynamic and accessible study method. However, the analysis showed that a portion of students continued to prefer traditional reading, suggesting that the podcast cannot be considered a universal method, but rather a complementary resource within multimodal teaching strategies. For this reason, it would be wise to adopt approaches that combine podcasts with written and visual materials, in order to respond to the different needs and learning styles of students.

Another significant element concerns group work. The data confirm that the creation of podcasts has fostered collaboration between trainees, strengthening discussion and shared work. However, some organisational difficulties limited the full effectiveness of the activity, particularly with regard to the division of roles and time management. In order for podcasting to be used more effectively within teaching, it is necessary to provide support tools for the management of collaborative work, providing clear and structured guidelines for the assignment of responsibilities within groups.

From a methodological point of view, an important limitation of the study concerns the fact that the evaluation of the impact of podcasting on learning was conducted exclusively through subjective perceptions, without tools for direct measurement of the results obtained. For future research, it would be useful to integrate objective assessment methods, for example through pre- and post-activity comparative tests, or by comparing the results of students who used the podcast with those who followed more traditional teaching approaches.

In conclusion, the results obtained suggest that podcasting can represent an innovative and effective tool for university learning, especially if integrated with flexible teaching strategies and adequate tools for the management of group work.

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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.

KEYWORDS Cognitive Performance; Learning Improvement; Innovative Environment.

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.

Parole chiave Performance Cognitiva; Ambiente di Apprendimento; Ambiente Innovativo.

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: Augmented Reality 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.

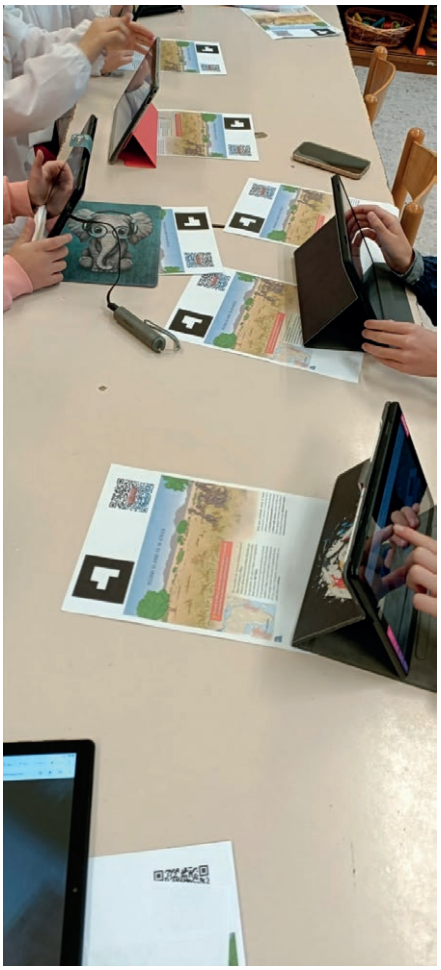

Figure 1. Children using AR during lessons.

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).

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 proce-

dures 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 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 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).

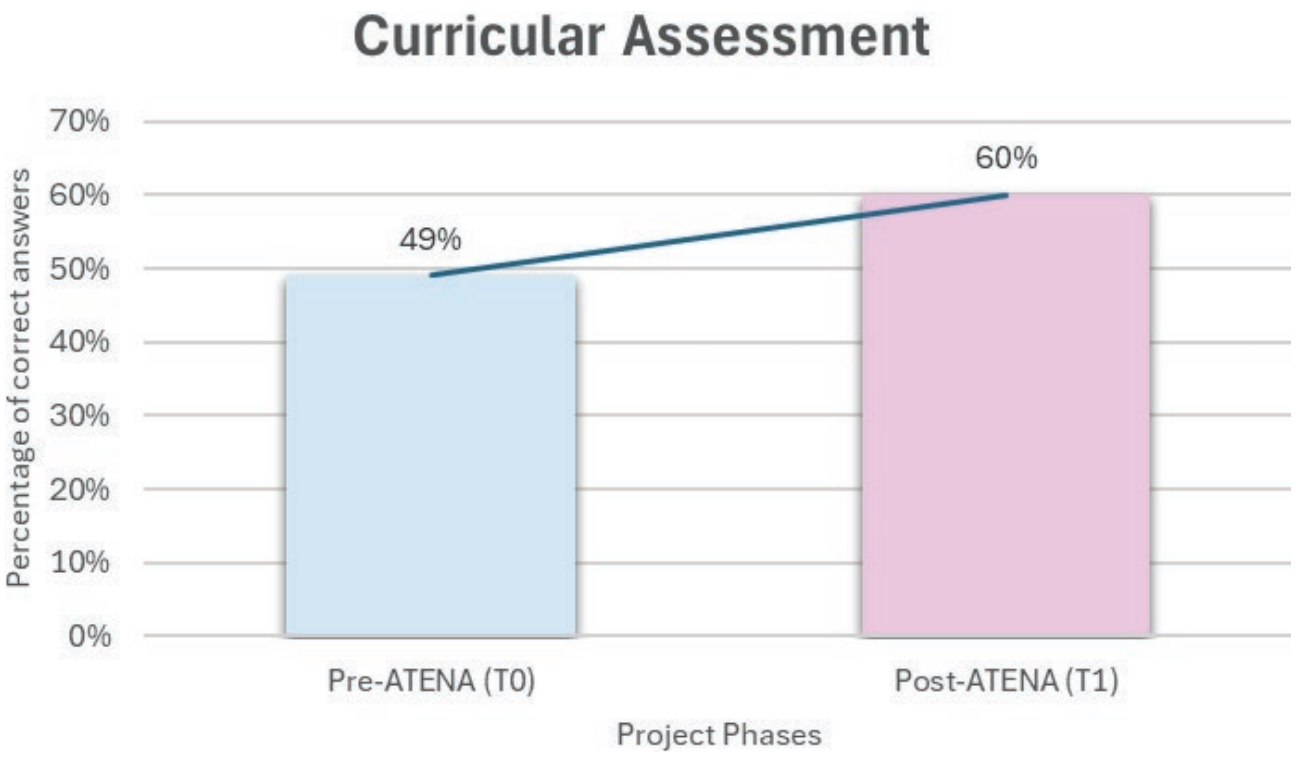

Figure 2. Curricular assessment.

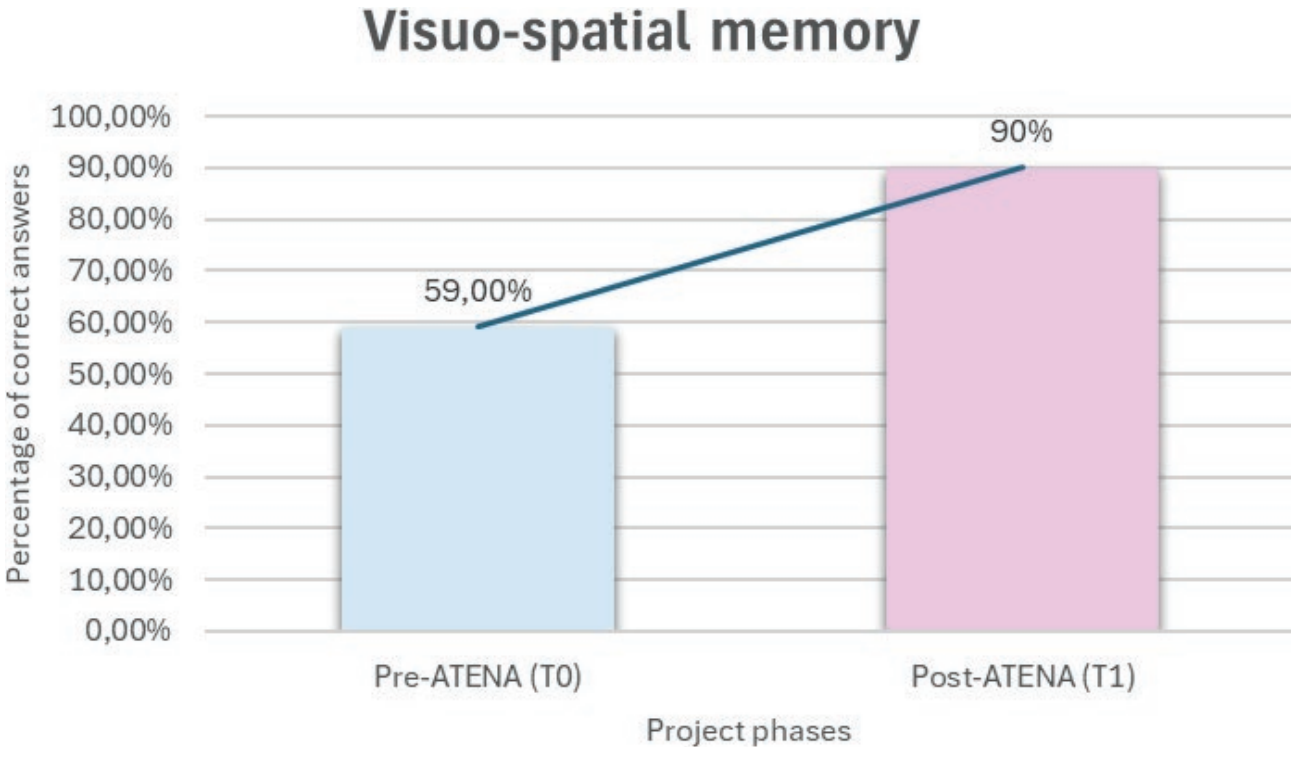

Figure 3. Visuo-spatial memory.

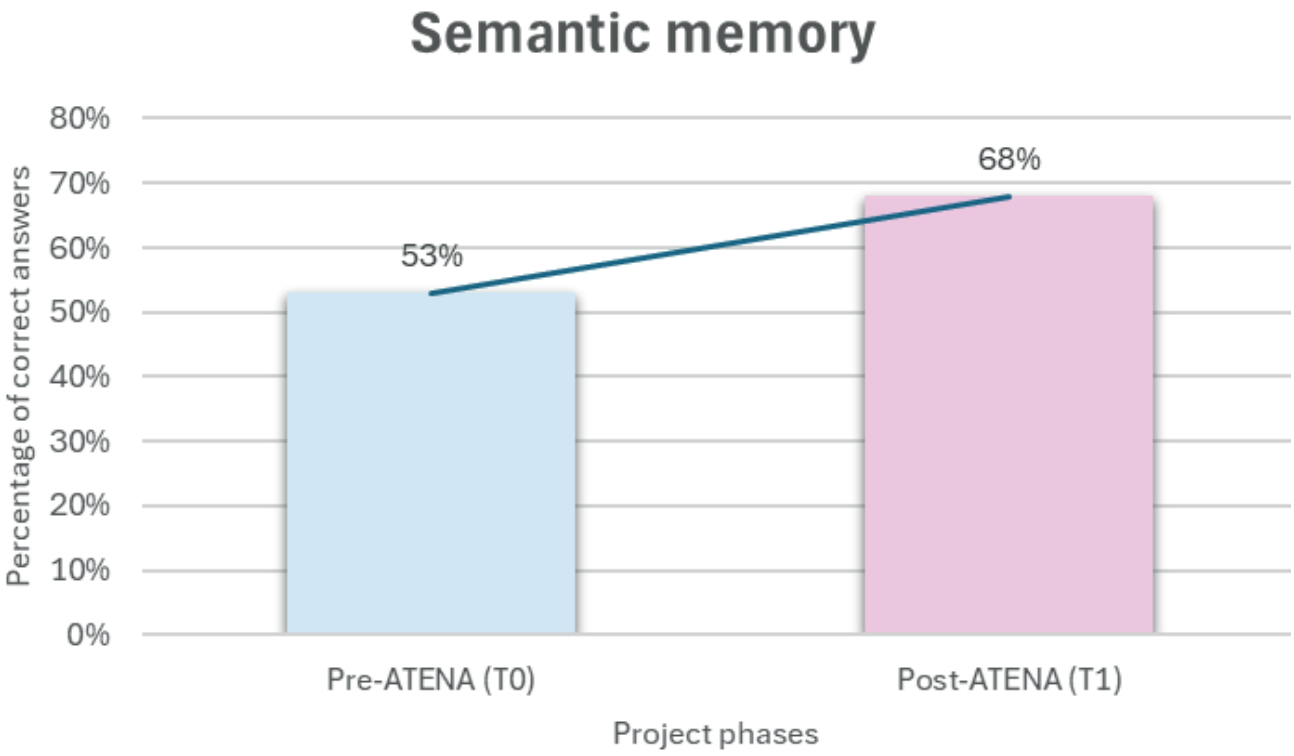

Figure 4. Semantic memory.

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, 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.

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.

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 2. H1 Paired sample t test.

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

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 4. H2 Paired sample t test.

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

4.5.2. H2 – Visuo-spatial Memory

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

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.

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 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.

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.

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 6. H3 Paired sample t-test.

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

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. Conclusions

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

This work represents the result of a collaborative effort among the authors. Luna Lembo drafted Sections 1, 1.1, 1.2, 3, 4.6, and 5. Elèna Cipollone drafted Sections 2, 4, 4.1, 4.2, 4.3, and 4.5. Francesco Peluso Cassese supervised the research project. All authors contributed to the final revision of the manuscript and approved the submitted version.

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Toward a new paradigm of AI-powered programming education through metacognition

Verso un nuovo paradigma per la didattica della programmazione con l'AI attraverso la metacognizione

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ABSTRACT The introduction of generative Artificial Intelligence (AI) in programming and computer science education has raised numerous concerns about its impact on learning. While professionals increasingly rely on it to enhance productivity, students and teachers face challenges in adapting to this tool, often viewed as "cheating." In this study, we explored these issues with the aim of validating a teaching practice capable of fostering higher-order thinking skills such as metacognition, creativity, and critical thinking, which are often overlooked in traditional computer science education. Involving 40 students in an AI-powered programming activity, the research explored problem-solving with AI-generated code. Pre- and post-surveys revealed significant improvements in competencies, AI literacy, and metacognitive reflection. Results suggest that integrating AI strategically can enrich programming education by fostering critical skills for the modern era.

KEYWORDS AI-aided Education; Metacognition; Problem-Solving; AI Literacy; AI in Programming Education.

SOMMARIO L'introduzione dell'intelligenza artificiale generativa nell'ambito della programmazione e della didattica dell'informatica ha posto numerosi dubbi sul suo impatto sull'apprendimento. Se da un lato, le aziende incoraggiano l'adozione di questo strumento da parte dei loro dipendenti al fine di aumentare la produttività, studenti e insegnanti affrontano sfide nella sua integrazione, spesso percependolo come una scorciatoia. In questo studio abbiamo approfondito tali questioni con l'obiettivo di validare una pratica didattica abile nel valorizzare le higher-order thinking skills come metacognizione, creatività e pensiero critico, spesso trascurate nella didattica tradizionale dell'informatica. Con questo obiettivo, abbiamo quindi coinvolto 40 studenti in un'attività di programmazione con l'uso dell'IA, raccogliendo dati e analizzando il processo di problem-solving con codice generato dall'IA. I dati raccolti dai questionari pre- e post-attività hanno presentato effetti significativamente positivi dell'attività su competenze, AI literacy e riflessione metacognitiva. I risultati suggeriscono quindi che l'integrazione strategica dell'IA può costituire un valido potenziamento per la didattica favorendo il potenziamento di abilità chiave non solo per l'apprendimento ma anche per la carriera futura.

PAROLE CHIAVE Educazione Supportata dall'IA; Metacognizione; Problem-Solving; Alfabetizzazione all'IA; IA nell'Educazione alla Programmazione.

1. Introduction

The integration of innovative tools based on generative Artificial Intelligence (AI) technologies has profoundly transformed the landscape of computing, reshaping both educational practices and professional workflows.

While in the past the core of Computer Science (CS) and Software Engineering was about manually writing the code, the introduction of Generative AI tools for coding such as OpenAi ChatGPT and GitHub Copilot has elicited a discussion about the aspects of programming and the skills behind it. Moving from "just" writing the code to having an agent taking care, at least partially, of the implementation changes drastically the role of the developer and the software engineer, and poses several concerns regarding work threats as well as how successfully CS education can adapt.

The introduction of Generative AI for programming has caught CS education off guard with the result of being perceived as a threat for learning quality and an easy and accessible way of cheating. On the other side, the work environment has strived to integrate it in the actual practice to enhance quality and developers team efficiency: fixing errors in time, addressing multiple options, spending less budget to deal with small issues (e.g. debugging minor errors, adding boilerplate code, input validation, etc.).

Despite industry's gradual adoption of Generative AI tools (Weber et al., 2024; Clear et al., 2024), which are redefining the roles of programmers and software engineers by reducing the necessity for manual code writing (Li et al., 2022), the educational system continues to regard their use as academic dishonesty and discourages such practices. This position arises from the fear that AI may negatively impact CS learning by facilitating cheating, rendering programming exercises less effective, and complicating assessment processes (Daun & Brings, 2023). From teachers' perspectives, AI is often seen as merely a shortcut. However, the literature argues that placing less emphasis on "*artisanal*" code calls more than ever for advanced expertise in related content and tools (AI algorithms, data science, machine learning, etc.) also known as AI literacy (Guzdial, 2022).

Despite the growing debate, a clear research gap remains: little is known about how the systematic integration of AI into programming education affects the underlying cognitive processes involved in learning to code – particularly metacognition and problem-solving strategies, which play a fundamental role in these tasks. To address this gap, the present study asks: *What is the impact of engaging with AI-generated code on students' problem-solving processes, metacognitive reflection, and AI literacy in programming education?*

To answer this question, we conducted a quasi-experimental intervention using a mixed-methods approach, combining qualitative and quantitative data to capture both educational and cognitive outcomes. The contribution of this project lies in providing empirical evidence on how AI-driven programming practices influence key cognitive processes, thereby offering a clearer understanding of their role in fostering metacognition and problem-solving in computer science education.

2. Background

The background of this research articulates across the dimensions of the programming task, the concept of metacognition in the context of Higher Order Thinking Skills, (Veenman et al., 2006) the state of the art of AI in education, the concept of AI literacy and how these apparently separated topics lies in common ground of problem solving and expression in natural language.

2.1. Abstracting programming

To best frame the topic, it is important to begin by defining computer programming. At its core, computer programming is about creating a sequence of instructions that the computer must follow in order to perform a specific task. This process involves first designing algorithms–high-level descriptions of solutions to specific problems–and then coding them into precise instructions for the computer to execute, written in any of the programming languages available. Programming has Computational Thinking (CT) at its heart, which refers to the mental process of "*Computational thinking involves formulating problems and expressing solutions in a way that they can be effectively executed by an external agent, whether human or artificial*" (Wing, 2006) and it constitutes a specific niche of problem-solving, where a third agent is involved in the execution of the solution.

Programming can then be seen as a process centered on the structured articulation of both the problem and its solution. The problem is carefully broken down into smaller, more manageable parts, in order to identify patterns, while the algorithmic solution is systematically designed to ensure a clear, efficient and accurate execution by a third party. This approach emphasizes a problem-solving methodology that places greater focus on the expression aspect, offering intriguing implications for the underlying logical reasoning. For instance, in a visual-perceptual reasoning problem, the solution typically revolves around the implementation. In contrast, programming requires the precise expression of the solution process using the syntax and tools specific to each programming language.

2.2. Higher order thinking skills, problem-solving and metacognition

Within Educational Psychology, Higher Order Thinking Skills (HOTS), problem-solving and metacognition encompass a complex interplay of processes and cognitive abilities that profoundly influence students' learning outcomes (Sulistiyani et al. 2022).

More in detail, HOTS involve advanced cognitive abilities such as analysis, evaluation and creativity, which are supported by metacognition and play a special role in problem-solving processes (Sengul, S., & Katranci, Y, 2012). In contrast, lower-order thinking skills (LOTS) focus on basic cognitive functions such as memory and comprehension. In this framework, LOTS enable students to recall and reproduce information, while HOTS are crucial for elevating the learning process by enhancing the quality and originality of the information processing (Rianti et al., 2024).

On the same line, metacognition is defined by Cornoldi (2002) as "*a state of knowledge on the functioning of the mind*". It includes a set of intertwined processes such as planning and orientation, problem definition, evaluation and regulation.

Despite acknowledging the importance of this triad, the educational system struggles in integrating effectively opportunities focused on these aspects. Furthermore, the current debate highlights shortcomings in this area, particularly in assessment practices, which remain predominantly centered on LOTS-based learning (Rianti et al., 2024).

In this context, a strong link between CT and metacognition is constituted by the deliberate development of strategies, combined with the process of articulating the solution that can be implemented by a third agent (Yadav et al., 2022; Goldstein & Papert 1977).

2.3. AI in Computer Science education

The integration of AI into education poses multiple challenges at both the policy and practice levels, as highlighted in the taxonomy of AI in Education proposed by Ranieri et al. (2023). These vary

across disciplines and regard questions of curriculum design, assessment practices, and the broader implications of AI for teaching and learning.

In the case of CS education, framing these challenges requires focusing on the core component of CS curricula, which integrate knowledge from programming, algorithms and data structures, and software engineering into the act of writing code to solve a programming problem/exercise. In this context, AI, unlike many other disciplines, can play a particularly instrumental role in providing suggestions, recommendations, and support in addressing both error messages and bugs (Verleger, M., & Pembridge, J, 2018; Lo, 2023). Concretely, this may involve chatbots that suggest solutions, fix errors, or even generate working code, a capability that simultaneously raises concerns and fears of misuse.

To address this concern, recent literature shows a growing interest in finding ways to take advantage of this tool while preserving academic integrity and learning quality. This has led to the identification of analogies between AI application and established educational practices.

A notable example is the comparison between code tutoring tools and traditional practices of peer-to-peer learning (Banić et al., 2023; Han et al. 2010). Similarly, several studies have likened the use of AI to pair programming (Zhang et al., 2022), in which two programmers work collaboratively on the same code, with one acting as the *driver* responsible for writing the code and the other as the *navigator*, providing guidance and feedback. In this context, AI in computer science education presents an opportunity to enhance these techniques (Garcia et al. 2024) by providing higher quality and more effective support for the learning process (Ma et al. 2023; Manfredi et al. 2023).

2.4. AI literacy and education

AI literacy encompasses the knowledge, skills, and competencies required to effectively engage with artificial intelligence. Using a car analogy, literacy involves understanding the parts and functioning of the car to drive it consciously. Unfortunately, AI literacy and AI education are often misunderstood as interchangeable concepts. However, they differ: AI literacy refers to the knowledge within a competency framework for AI, while AI education focuses on the practical application of that knowledge (Ojeda-Ramirez et al., 2023).

Concretely, AI knowledge includes understanding concepts such as what a Large Language Model (LLM) is, how it operates, and its broader implications, including ethical considerations. For example, recognizing that an LLM functions by calculating the most probable word to output for a given input significantly influences how we interpret and value the information it generates (Tate et al., 2023). Additionally, a competency framework may include skills like prompt engineering and understanding which AI applications are suitable for various contexts, providing guidance for their practical and effective use.

The educational implication is that a solid understanding of what AI is – acquired either before engaging with AI or alongside practical experiences – is essential to enable individuals not only to use AI but to do so consciously, understanding both the possibilities and limitations of this technology (Ojeda-Ramirez et al., 2023; Kulik & Fletcher, 2016).

2.5 Problem solving and its expression in natural language

Problem-solving is a multifaceted process that involves the interplay of knowledge, strategies, insights, and much more. According to the framework proposed by Sulistiyani et al. (2022), it includes

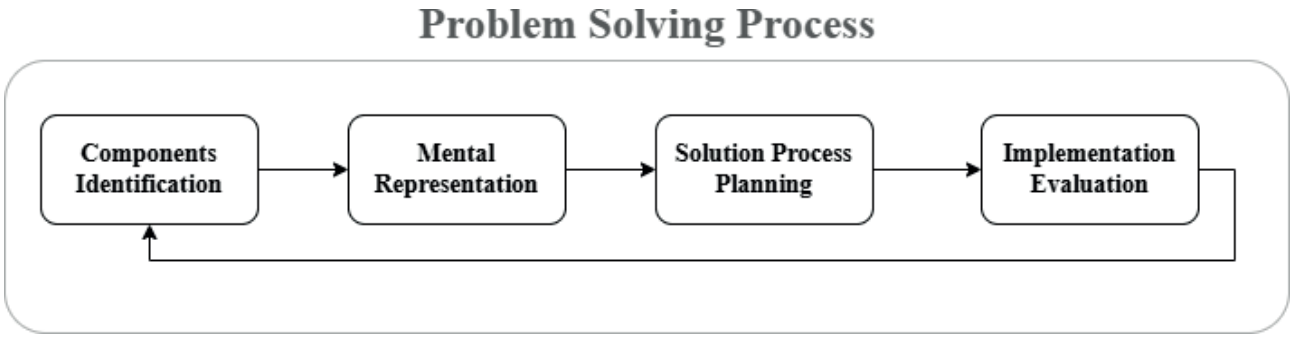

Figure 1. Components of the Problem-Solving process according to Sulistiyani et al. (2022).

several key components: problem identification, mental representation, solution process planning, and the evaluation of implementation (Figure 1).

1) *Component identification* involves defining the data and requirements for the given problem. This step is crucial for the success and efficiency of subsequent phases. Misidentifying problem data or incorrectly formulating the problem can significantly hinder the solution process (Skalicky et al., 2017).
2) *Mental representation* is a critical aspect of problem-solving, applicable even to problems that may initially seem too abstract to conceptualize. It involves forming an abstract understanding of the goals and requirements to navigate potential paths toward a solution (Raiyan et al., 2023).
3) *Solution process planning* refers to adopting a structured approach to achieve the desired outcome. This phase is heavily influenced by the specific discipline and its associated techniques (Sengul & Katranci, 2012).
4) *Implementation and evaluation* of the solution in this context involve writing the code and ensuring it runs successfully without errors. In programming and computer science, the evaluation primarily focuses on assessing the functionality, efficiency, and correctness of the code.

The process of problem-solving, both as a whole and in its individual components, is closely tied to natural language and, more broadly, verbal, written, and linguistic expression. In most educational contexts, problems are presented as written descriptions, which can vary in syntactic and narrative complexity. In this setting, verbal reasoning and linguistic intelligence serve as key catalysts during the initial stages of problem-solving, even in subjects like mathematics (Raiyan et al., 2023).

Discursive skills are essential for understanding and articulating problems. Beyond this, they can play a pivotal role throughout the problem-solving process by fostering creativity and enhancing the quality of reasoning (Darwis et al., 2024). Linguistic features, in particular, can significantly support mental representation and navigation by making explicit the heuristics, impulsive reactions, and ambiguities that the solver might not be fully aware of (Raiyan et al., 2023).

On a final note, the background of this research underscores the interplay between programming, higher-order thinking skills, and metacognition within the broader field of AI in education (Kittel & Seufert, 2023). While AI literacy provides the essential foundation for engaging effectively with new technologies and tools, programming itself remains deeply rooted in problem-solving through linguistic expression. Merging these perspectives reveals a common ground on which to build innovative educational practices.

3. Method

In light of the current debates surrounding skills and computer science education in the era of AI (Verleger & Pembridge, 2018), the concepts presented in the background section can be organically interrelated to create a vision of integrated activities and learning goals. This perspective does not merely address technical skills but also incorporates AI literacy and learning meta-processes, including cognitive skills.

With this aim, we conducted an interventional quasi-experimental study where students were required to solve problems exclusively using AI-generated code, without the possibility of manually editing the code. The problem set included 5 simple programming tasks suitable for first-year computer science students who had completed an introductory programming course; 5 algorithmic problems appropriate for second- or third-year students with prior coursework in algorithms and data structures; 5 parallel programming tasks, representing a topic not typically covered in basic courses; and 1 olympiad-level problem, included to ensure that students would not run out of challenges before the end of the activity.

We employed a custom web platform that mediates all interactions with large language models and enforces the "AI-only" constraint of the intervention. The system provides a shared workspace for each group, manages multiple LLM back ends through a unified API, and records complete prompt–response logs with timestamps to enable fine-grained analysis. It also supports task-level constraints (e.g., blocking manual code edits, surfacing error messages) and basic analytics dashboards for monitoring activity during the sessions. A detailed description of the architecture, logging pipeline, and constraint enforcement is available in (Paludo et al., 2025).

The study was designed to address the following research question: *What is the impact of engaging with AI-generated code on students' problem-solving processes, metacognitive reflection, and AI literacy in programming education?*

In this framework, we formulated hypotheses across three interconnected dimensions:

- Problem-solving
  - *Hypothesis 1*: Solving exercises solely with AI can enhance specific components of problem-solving, including problem decomposition, solution planning, and evaluation of implementations.
- Metacognition
  - *Hypothesis 2*: This type of intervention can stimulate an attentional shift (Metcalfe & Scimamura, 1996) in students, moving their focus from the problem itself to the meta-process of its solution.
  - *Hypothesis 3*: AI can function as a medium that fosters the development and enhancement of metacognitive skills, encouraging students to monitor and reflect on their reasoning strategies.
- AI Literacy
  - *Hypothesis 4*: Intensive and supervised use of AI in programming tasks can foster a clearer perception of the tool's strengths and limitations.

Although collaboration was not part of the primary research question, it was included as an additional dimension. Since the intervention was conducted in groups to attract student participation, it was important to explore how group dynamics interact with AI use in programming education.

- Collaboration
  - *Hypothesis 5*: Working with AI in group settings can support team collaboration and mitigate unbalanced dynamics where a single member undertakes most of the work.

3.1. Participants

The sample consisted of forty students (N = 40) recruited from the Department of Computer Science at the University of Trento (N = 20) and the University of Innsbruck (N = 20). Participants applied to take part in the project and were selected based on motivation and academic merit. Following the data cleaning process, only those who fully completed the survey were included in the analysis (N = 34; Table 1). The distribution of students across the programs – BSc in Computer Science, MSc in Computer Science, and MSc in Software Engineering – is detailed in Table 1.

During the intervention, participants were organized into groups of 3–4 members, ensuring diversity in backgrounds. Each group included at least one student from each education level, and participants were arranged to ensure not everyone in the group spoke the same language.

With respect to expertise and prior experience with AI for programming, the selected students reported having some experience, primarily limited to addressing error messages (e.g., understanding their meaning) and quickly fixing typos or simple bugs (e.g., missing commas). Participants self-rated their experience with AI for programming on a scale from 1 ("None") to 5 ("Highly Frequent User"), with an average score of 3.08 (SD = 1.09).

Table 1. Sample's distribution in different courses.

Course	BSc in CS	MSc in CS	MSc In Software Engineering	Total Participants
Frequencies	17	9	8	34

3.2. Data collection procedure

The activity spanned two days, in which students engaged in solving a series of programming exercises on a platform developed specifically for this initiative.

The programming exercises varied in difficulty and included specific constraints (e.g., avoiding the use of a particular function that the AI would typically employ by default). It was crucial to design the exercises with elements of ambiguity. By ambiguity, we refer to nuances of meaning and implicit concepts that AI systems might overlook or misinterpret. For example, when addressing a competition scenario, we understand that a final ranking might include ties when two or more participants achieve the same performance. For AI, such nuances represent unexpected elements during the solution process, often leading to errors that impact the outcome.

The data collection protocol, outlined in Figure 2 and detailed in Table 2, consisted of the following steps:

- *Pre-activity survey*: Designed to gather information on students' demographics, expertise with programming languages, AI literacy, and experience using AI for programming.
- *Observational data*: Collected in two ways: expert observations during the activity and video recordings of two selected groups. The video recordings were conducted via Zoom (Version 6.00.0), capturing both group interactions and screen activity.
- *Interaction logs*: A detailed record of all interactions between the groups and various AI engines, collected through the dedicated platform provided to the students.

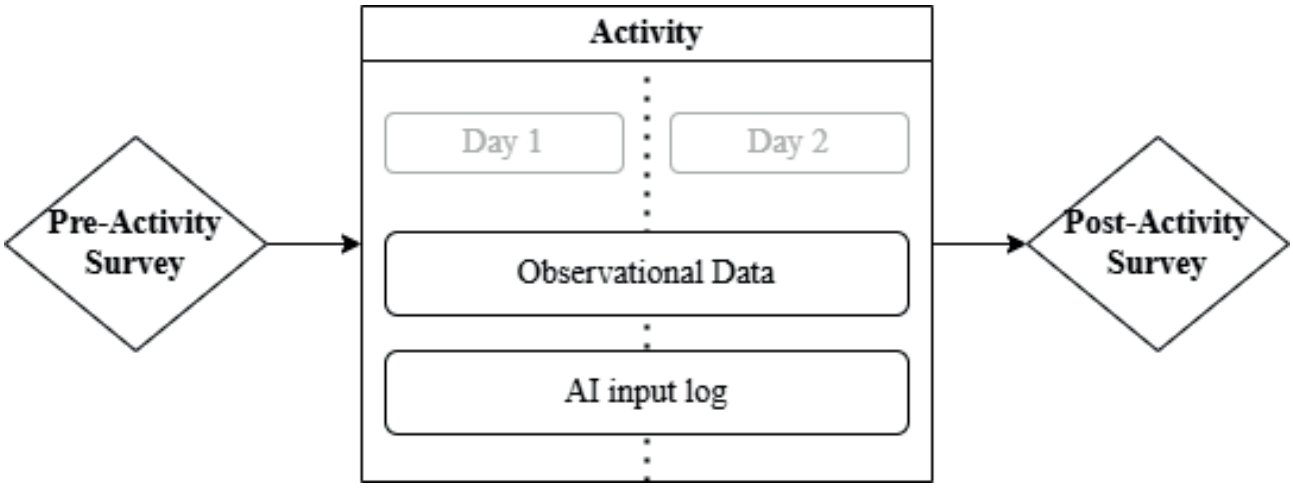

Figure 2. Data collection procedure with a pre-post activity survey and the collection of observational data and AI input log during the activity.

– *Post-activity survey*: Focused on self-evaluation of skills and participants' perceived learning about and with AI.

3.3. Measures and variables

The study included a combination of self-report and behavioral measures to address the following constructs:

– *AI Literacy*, given a proper and clear definition of the construct according to Ojeda-Ramirez et al., (2023), was rated by the respondents on a scale from 1 to 10. Internal reliability was satisfactory (Cronbach's $\alpha = .72$).
– *AI Impact on Skills* intended as the level of impact in positive and in negative the use of AI has on core skills for learning (critical thinking, problem solving, creativity, team collaboration, adaptability to complex situations - Verleger & Pembridge, 2018) was rated by respondents on 5 items with a scale from 1 "Highly deteriorated" to 6 "Highly improved" (Cronbach's $\alpha = .90$).
– *Problem approach* as the procedure and strategies' quality were assessed by asking respondents to describe the steps they would take to solve the problem. The open-ended responses were then analyzed by 3 researchers separately with consistent agreement.
– *Metacognition* was assessed both qualitatively with an open-ended question and quantitatively with a reduced version of Biasutti & Frate's scale for metacognitive processes (2018) which had adequate internal reliability as well (Cronbach's $\alpha = .73$).
– *Problem Solving* components according to the framework proposed by Sulistiyani et al. (2022), were assessed through 8 items on a 7-point Likert scale with adequate internal reliability (Cronbach's $\alpha = .75$).

As the data were collected in a quasi-experimental design, the analyses followed a pre-post comparison with paired sample T-test and the dependent variables tested included:

– AI Impact on Skills
– AI literacy

Table 2. Data collection methodology overview; for a highly detailed description of the employed protocol, see (Paludo et al., 2025).

Method	Content	Purpose
Pre-Activity Survey	– Demographics – Previous knowledge and current use of AI for coding – Current AI literacy – A sample problem to be approached without AI – Perception of the current use of AI impacts learning	– Self-assessment of familiarity and experience with AI tools in programming – Self-evaluation of participants' understanding of AI concepts – Evaluating the solving approach to a coding problem without AI – Perception on how the current AI usage may impacts learning
Post-Activity Survey	– Perceived learning on AI for coding and AI literacy – Problem approach with the use of AI as in the challenge – Perception of a shift in attention and metacognitive reflection – Describing how the activity's tasks of programming only with AI felt through a metaphor; – Components of problem-solving in relation to AI and without AI – Metacognition in the group according to a reduced scale of Biasutti & Frate (2018)	– Assessing changes in AI literacy and knowledge – Identifying a change of approach in solving problems – Analysis of AI as a medium of metacognition processes and reflections; – Assessment of problem-solving processes with and without AI – Analysis of the metacognition processes in the group according to a reduced Biasutti & Frate's scale (2018)
Observational Data	Video recording (webcam and screen recorder) of 2 volunteer teams during the whole challenge.	Analysis of interaction according to Powell et al. framework (2003), groups dynamics and out loud reasoning
Chat Log	Log of all the queries submitted to the different LLMs by the participants.	Structures and strategies of prompt engineering.

– Problem Solving components
– Metacognition.

4. Results

Overall, the data analysis revealed interesting and positive outcomes from the intervention, highlighting improvements in competencies. The results are presented in two sections: one focusing on quantitative analysis and the other on qualitative analysis.

4.1. Quantitative results

A more detailed overview of the data, including the statistical analysis, is presented in Table 3.

– *AI Impact on Skills*. The integration of AI-generated code in the setting of programming education, enhances the skills of critical thinking and team collaboration. Compared to the scenario of this setting with AI and without AI, participants reported the positive impact of AI on critical thinking ($p < 0{,}036$) and team collaboration ($p < 0{,}001$). Creativity and adaptability to complex situations are not significantly impacted by the use of AI.
– *AI Literacy*. Participants' self-rated AI literacy showed a significant improvement following the supervised and intensive use of AI during the intervention ($p < 0.017$).

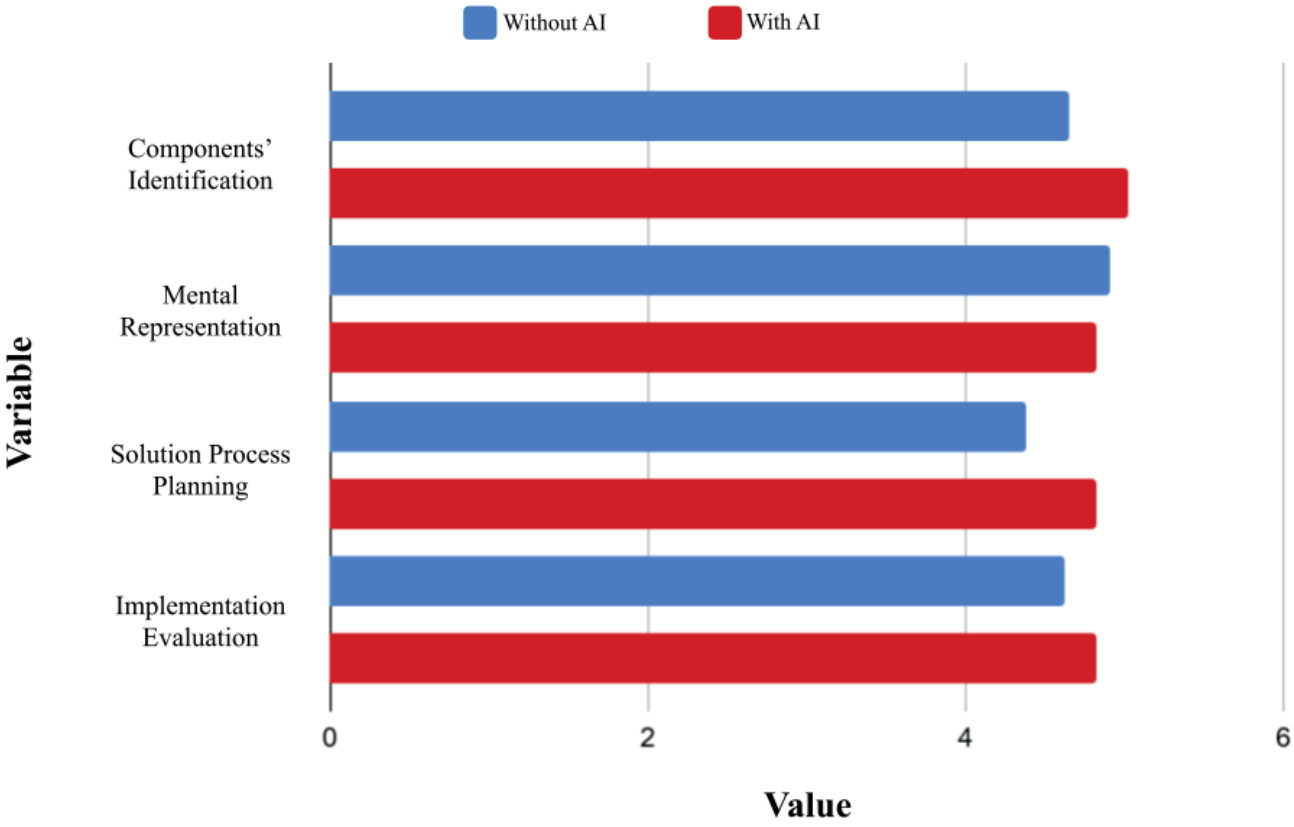

Figure 3. The paired column graph illustrates students rating the four dimensions of problem-solving (Components' identification, Mental Representation, Solution Planning Process and Implementation Evaluation). For each dimension, the blue column shows participants' rating for the problem-solving process Without AI, while the red column indicates the same but in the condition with AI.

- *Problem Solving Components*. The statistical analysis revealed that AI has varying effects on the components of problem-solving. Specifically, component identification ($p < 0.022$) and solution planning ($p < 0.029$) showed significant benefits from the use of AI (Figure 3.). In contrast, other components, such as mental representation and evaluation, appeared unaffected by the integration of AI.
- *Metacognition*. AI was observed to stimulate an attentional shift from solution implementation, such as code writing, to deeper reasoning during the early stages of problem analysis. This shift was particularly evident in the process of aloud reasoning and the formulation of effective prompts.

4.2. Qualitative results

4.2.1. Problem approach

The question that required participants to describe the solution process both with and without AI enabled a direct comparison of the two approaches, highlighting significant differences in the impact of AI assistance.

Table 3. Statistical analyses of questionnaire data with variables, statistical methods employed, computed values, degrees of freedom (dof), and significance levels ("**" = significance < .05). H_a μ Measure1 - Measure2 < 0.

Variable		Test	Value	dof	p
AI Impact on Skills	Critical Thinking	Student T-test	-0,617	33	0,026**
	Creativity	Student T-test	-0,153	33	0,088
	Team Collaboration	Student T-test	-0,344	33	<0,001**
	Adaptability to Complex Situations	Student T-test	0,468	33	0,519
AI Literacy	AI Literacy	Student T-test	-2,040	33	0,017**
Problem-Solving Components	Identifying a problem's components (M1 = without AI, M2 = with AI)	Student T-test	-0,688	33	0,022**
	Mentally represent the problem without and with AI(M1 = without AI, M2 = with AI)	Student T-test	0,288	33	0,458
	Understanding how to plan the process to solve a problem (M1 = without AI, M2 = with AI)	Student T-test	-0,588	33	0,029**
	Evaluating the solution to a problem (M1 = without AI, M2 = with AI)	Student T-test	-0,057	33	0,109
Metacognition	Attentional Shift Perception	χ^2 Goodness of fit	11,2	33	0,048**

Problem approached without AI. The "traditional" approach to solving a programming problem involves a step-by-step process driven entirely by human reasoning. It begins with carefully understanding the problem, ensuring clarity on the data, requirements, and constraints. This is often followed by visualizing the problem, sometimes using paper, to break it down into actionable tasks.

Next, a strategy is formulated. For the specific problem presented, common approaches include *brute force, greedy optimization* or *divide-and-conquer*. Once a potential solution is defined, the individual manually tests simple cases, iterates to refine the code, and debugs while optimizing for efficiency.

This problem-solving process relies on a strategic combination of intuition, prior expertise, and knowledge gained from solving similar problems.

Problem approached with AI. With the use of AI, the initial steps of problem-solving change significantly. After a brief and often superficial reading of the problem, many participants directly copied and pasted the problem statement into the LLM. The first output is commonly taken as an initial draft to better understand the problem and explore how to guide the model more effectively in meeting constraints and requirements.

Instead of manually writing the code or generating detailed steps, most of the effort in this approach shifts to a process of iterative editing and debugging. This involves a more in-depth analysis of the problem structure to break it down into a detailed sequence actionable by the LLM (Lowe, 2019). The focus is primarily on optimizing interactions with the AI, refining the prompts, and improving the code's efficiency through collaborative iteration with the model.

4.2.2. Metacognition and metaphors

The analysis of responses to the open-ended questions regarding reflections on the experience through the use of metaphors and descriptions of personal mental effort shed light on how the use of generative AI for programming can enhance metacognition.

The key themes that emerged from the analysis include: a shift in cognitive focus, metacognitive reflection, the impact on problem understanding, collaboration with AI as a cognitive partner, and improvements in efficiency.

Metacognitive Reflection. Respondents highlighted how explaining the problem and solution to a LLM in order to generate the correct code significantly aided their ability to monitor and evaluate their own thought processes, drawing parallels to teaching and pair programming. Using generative AI for programming in such an intensive manner created a feedback loop that stimulated self-evaluation. As one participant noted "*It's like pair programming, where you correct yourself as you say what you are doing*". Additionally, this approach fostered deeper problem understanding, as another respondent remarked, "*It brings a deeper understanding by having to help someone to get an idea for a problem*".

Furthermore, the feedback loop encouraged participants to engage in a reiterative process of self-evaluation, prompting them to think critically about the strategies and approaches they employed. This process also led them to reflect on how effectively they were expressing their ideas and identifying the best way to communicate their solution and strategy. As one participant explained, "*You need to think how the chatbot can get to the solution I have in mind*".

Impact on Problem Understanding. Not being able to write code by yourself adds additional cognitive effort, as it requires translating the envisioned solution into natural language to explain the problem effectively (Denny et al., 2024; Denny et al., 2023). This process fosters a deeper comprehension of the problem, as students emphasized before moving on to solution implementation: "*You always have to understand the problem yourself, then you shift your focus to approaches.*" However, the challenge of interacting with AI also led some students to focus more on developing effective prompts rather than fully understanding the problem. As one participant noted, "*You don't focus on understanding the problem but instead on the prompt and how to interact with the AI*". This highlights the dual nature of the AI interaction, where balancing problem understanding and prompt formulation becomes a critical skill.

AI as a Cognitive Partner. The aspect of co-creating solutions made some respondents interact with AI in a collaborative and guided manner, steering AI's responses in the right direction avoiding the strategy to only impose their view but "We *started with throwing the problem statement at the AI and working from there, analyzing how it approached the problem*". Moreover, the aspect of guiding the AI solving the problems required setting shared standards between the participants and the LLM in order to have AI get their perspective as reported "*The challenge becomes making the AI understand what we are thinking and how we are solving it*".

Efficiency Trade-offs and Negotiation with AI. For the initial problems, AI appeared quite capable of addressing the problems; however, as the activity progressed and more complex problems were introduced, inefficient code became increasingly problematic. Participants noted that the time spent explaining their ideas to the AI often exceeded the time it would have taken to write the code manually, as one remarked: "*Explaining your idea takes longer than just programming*". This aspect of the experience highlighted the tool's limitations and reinforced the notion that AI in this context can be a double-edged sword – highly useful, yet demanding significant and reflective effort. As one student observed, "*You have to explain how to approach the problem, not just make the request*".

Learning through Explanation. The core of the metacognitive dimension in this activity lies in the reflective process required by generative AI programming, which parallels the act of teaching. This approach embodies the timeless principle that explaining something is one of the most effective ways to learn. It necessitates a deep understanding, the segmentation of one's abstract reasoning, and an awareness of the recipient's perspective. Respondents emphasized this aspect with statements such as,

"*The best way to learn something is to teach it*" and "*It helps to understand by having to process your own thoughts at a different level*". Additionally, the exploration of alternative problem-solving strategies fostered creative thinking and heightened metacognitive awareness of the strategies used. As participants noted, "*It forces you to think outside the box and try different approaches*" and "*The focus is on how you solve problems and manage data, not just coding*".

5. Discussion

The results of this study indicate that interventions utilizing exclusively AI-generated code in programming education can positively impact learning outcomes. These include not only programming skills and AI literacy but also other essential skills such as problem-solving, metacognition, and critical thinking.

From an overall perspective, programming with AI-generated code can be seen as a process of translating a solution or a set of insights into instructions using natural language. In its simplicity, this approach has proven to be a powerful practice that can be scaled to support learning across various contexts, from schools to academia and the workplace.

5.1. Hypothesis verification

Results are discussed by recalling the hypotheses generated.

Hypothesis 1. AI was associated with significant improvements in problem-solving, though its impact varies across different subcomponents: component identification, mental representation, solution process planning, and implementation evaluation (Figure 1). Specifically, problem decomposition ($p < 0.031$) and solution process planning ($p < 0.042$) show the most notable improvements with the use of AI.

This can be explained by the nature of the task, which demands greater attention to problem re-elaboration and precise planning to effectively draft a successful prompt. In this context, mental representation and implementation evaluation are less influenced by using AI, as the majority of effort is invested in systematic breakdown and sequential reasoning. However, the non-statistically significant difference ($p > 0,05$) in mental representation with and without the use of AI does not exclude its involvement in the task, since it mainly relies on internal cognitive schemas and prior knowledge, which AI cannot directly enhance but which plays a pivotal role in supporting other interconnected processes. Similarly, implementation evaluation appears comparable across conditions, suggesting a stronger reliance on user agency and only indirect support from AI (Chi & Wylie, 2014). Therefore, while AI significantly enhances the more procedural components of problem-solving, eliciting deeper cognitive reformulation and reflective evaluation, partial effects on other components cannot be excluded, as they remain integral to the task at hand.

Hypothesis 2. The process of "translating" a solution into an explanation that enables AI to generate the correct code induces an attentional shift in students from implementation aspects (code writing) to comprehension and solution planning. This attentional shift appears to foster metacognitive reflection, which significantly benefits from the use of AI ($p < 0.048$) by maximizing the focus on reasoning processes. This finding aligns with prior research emphasizing the role of externalizing reasoning through

structured explanations in supporting and enhancing metacognition in educational settings. In this context, the formulation of prompts serves as an effective intermediary for metacognitive scaffolding (Azevedo, 2005; Yadav et al., 2022). While externalizing reasoning can also be achieved through analogical means, the integration of AI in such tasks redistributes cognitive load. This redistribution reduces the effort traditionally spent on syntax and implementation details, reallocating it towards reasoning and problem re-formulation. As a result, higher-order thinking skills, such as critical analysis and creative problem-solving, are further developed and enhanced (Raiyan et al.; 2023).

Hypothesis 3. The task requirements and constraints compelled students to focus more on the meta-aspects of the problem-solving process, encouraging a deeper understanding of the underlying processes from an external perspective. However, this is achieved within the context of iterative interactions with AI tools, requiring students to translate their understanding into well-crafted prompts and critically evaluate AI-generated outputs. These activities systematically encourage students to monitor their thought processes and strategies, adjusting them as necessary (Azevedo, 2005; Prasse et al., 2024). The emphasis on meta-aspects is facilitated by the scaffolding brought to action by reflective prompts, feedback, and alternative pathways for approaching problems, further enhancing students' ability to self-regulate their cognitive and metacognitive strategies (Dabbagh & Kitsantas, 2012).

Hypothesis 4. Such an intensive experience with generative AI enhances AI literacy, making students more aware of the strengths and limitations of the tool they are using. This improvement is reflected in the evolution of the prompts they submit, as well as in their increasing effort to resolve ambiguities effectively. This observation aligns with studies that highlight the importance of proper training and supervised AI interactions in shaping users' algorithmic literacy and their ability to critically evaluate outputs (Folmeg et al., 2024).

Hypothesis 5. This type of activity, conducted in a setting with a single shared workspace (a group using one computer to access the platform for the task), significantly supports team collaboration ($p < 0.01$). Observational data further indicate that the requirement for teams to think out loud while drafting their prompts enhances communication and helps prevent misunderstandings. The collaborative learning literature highlights the benefits of distributed reasoning in group settings, which rely on effective verbalization of thought processes and the alignment of mental models (Resnick et al., 2015). The combination of a single shared workstation and the nature of the activity effectively fosters these positive dynamics, encouraging teamwork and improving collective problem-solving.

To provide an overview, the five hypotheses were examined with qualitative and quantitative results: while *Hypotheses* 1, 2 and 5 were supported by statistically significant empirical findings, *Hypothesis* 3 was supported both by qualitative data indicating stronger metacognitive engagement and also by quantitative data. *Hypothesis 4* was supported by statistically significant data. Together these results highlight both the strengths and limitations of AI-driven practices: while they clearly enhance specific components of the process, their support to other elements remains less valuable.

These results both align with and challenge previous research. On one hand, the outcomes of this project are consistent with the approach of integrating AI interaction organically into educational settings through a Socratic methodology (Gold & Geng, 2025; Cao et al., 2023). On the other hand, they challenge the assumption that such use of AI could foster a passive attitude toward coding (Daun & Brings, 2023).

5.2. AI powered metacognition and efficiency

As reported in results, the request for a metaphor to describe how the experience felt provided valuable insights into the educational potential of this approach. Responses such as, "You're trying to dissect your way of thinking and explain it step by step to the machine" along with similar variations, show the potential of this practice in enhancing metacognitive reflection and improving the quality of the initial stages of the problem-solving process. In this line, the emphasis on natural language expression and communication corroborates the thesis of AI as Intelligence Augmentation (Igelnik, 2011). The opportunity to engage with new programming languages, tools, and contexts allows learners to approach their reasoning from a different perspective, enriching their cognitive processes and problem-solving strategies.

The thematic analysis revealed that the use of AI in problem-solving prompts a significant shift in focus from direct solution implementation to explaining and delving deeper into thought processes. This kind of metacognitive engagement fosters greater flexibility in problem analysis and approach while also facilitating a deeper understanding that supports self-monitoring mechanisms.

From this perspective, AI acts as a tool to navigate and explore different strategies more effectively, promoting higher-quality cognitive engagement. It encourages reflection and heightens awareness of the importance of the initial understanding, regardless of the role played by AI assistance.

In regard to efficiency, AI can generate potential working solutions, including those that are slightly more advanced and would typically require more time to develop manually, even when based on relatively simple underlying concepts.

5.3. Limitations

The study acknowledges several limitations related to both the research design and the methodology employed, encompassing aspects of scientific inquiry and educational intervention.

While the methodology and intervention proved effective, they demand considerable resources, particularly for the use of LLM API services as well as the data collection and analysis processes. With a sample of only 40 students and approximately 10 workstations, the costs and data management were feasible; however, scalability could present challenges, particularly with increased expenses and resource demands. Additionally, technical constraints may need further attention to ensure the intervention remains practical and feasible on a larger scale.

Another limitation lies in the complexity of the data, which requires substantial effort to analyze. Despite this, the holistic nature of the methodology justifies these efforts by providing detailed and valuable insights into the educational outcomes and processes. In this connection, the sample, despite being aligned with the experimental design and resources allocation, could be considered not extensive enough.

Finally, it is important to acknowledge the exploratory nature of this study. The research question intentionally spans multiple dimensions (problem-solving, metacognition, and AI literacy) to capture the multifaceted ways in which AI may influence programming education. While this breadth allowed us to identify diverse effects and connections, it also limits the depth with which each construct could be examined. Future research should build on these findings by narrowing the focus to individual dimensions or by designing studies that address each construct with greater specificity.

6. Conclusions

Fulfilling the potential of a new support and enhancement to reasoning, while addressing the counterpart of fears for the loss of originality, can lead to a transformative approach able to elevate our thinking, much like the introduction of writing.

The main contribution of this project lies in the empirical demonstration that a strategic integration of generative AI into programming education, without affecting coding learning, can foster a broader set of skills, such as metacognition, problem-solving, and AI literacy, in. a different way. This work brings a new perspective on the debate about AI in CS education as a potential threat to learning quality by providing empirical evidence of how AI reshapes the balance between technical fluency and higher-order cognitive processes. Furthermore, this contribution provides practitioners with a framework to design interventions that exploit AI as a catalyst for reflection, planning, and collaborative problem-solving.

In the information era, the educational system is responsible for promoting programming and computer science not only as powerful tools for learning across disciplines but also as a means to empower the informed citizens of the future. With proper training and knowledge, AI can be leveraged not only for programming implementation but also as a catalyst for fostering code democracy. This approach would allow a broader segment of the population, including those without professional knowledge or expertise, to gain a better understanding of the underlying processes behind the tools they use every day. Society perceives programming as belonging only to a trained elite, which discourages many people from exploring it. Beyond the effects on the individual training, scaling the presented approach could promote a view of programming as "more accessible", thus democratising its use while preserving and adding more value to professionals' expertise (Beheshti, 2024). In essence, having a clearer understanding of how code is developed and what it calls for would allow people to be more informed about what they are interacting with every day and at the same time they would be able to better acknowledge the work carried out by professionals.

This study's insights motivate further research into this niche of educational innovation across different settings, bringing supporting points for the effectiveness of such practices for reasoning and higher order thinking skills enhancement.

Moreover, employing AI as a medium for upgrading manual programming, leads to more space for creativity and reasoning constitutes a tool that supports experts while also bridging and eliciting interest among the inexperienced.

At the individual level, oscillations in variables observed illustrate the concrete effects of transitioning "*from being code writers to code editors*" Paludo et al., 2025. Beyond the technical aspects, this shift has significant implications for enhancing problem-solving abilities and encouraging a more deliberate use of metacognitive strategies. In conclusion, this paradigm supports the development of key skills by fostering a powerful alliance between the learner and the tool. It promotes an appropriate level of dependence to enhance performance while mitigating the risks of overreliance. This dual impact, strengthening both technical fluency and cognitive self-awareness, not only improves the quality of learning outcomes and overall expertise but also establishes a foundation for a more thoughtful and adaptable approach to learning and problem-solving in an ever-evolving technological landscape.

On a final note, this study contributes with empirical evidence to the ongoing debate on AI in education by providing insights into how AI can be strategically integrated in CS education as a tool to augment metacognitive engagement and problem-solving while providing students with a training aligned to companies' approaches.

7. Author contribution

G. Paludo was responsible for experimental design, data collection, statistical analysis and main manuscript writing and A. Montresor managed the project logistics, coordination and implementation of the project as well as writing the article.

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