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Special Issue
Extended education in a technology augmented world

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

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Editorial. Extended education in a technology augmented world

Editoriale. Educazione estesa in un mondo tecnologicamente aumentato

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Extended Education is an evolving and dynamic concept that leverages advanced technologies to transcend traditional educational boundaries in terms of learning contexts, methods and geographical areas. In this technology-augmented world, education is no longer confined to formal education and traditional education settings and paths; instead, it encompasses various learning contexts, including informal learning environments, higher education and lifelong learning (LLL). Extended education promotes the creation of a borderless and inclusive educational landscape, particularly with the development of internationalisation through virtual mobility (BIP, COIL, etc.) and the emergence of micro-credentials. Technologies such as Virtual Reality (VR), Augmented Reality (AR), robotics, and Artificial Intelligence (AI) are key tools driving this transformation, offering new learning methods reinforcing flexibility for learners and new avenues for skills development and for personalised, inclusive, and accessible learning (Benkhalfallah et al., 2024; Samala et al., 2024). Technology enhances educational access and quality in marginalised and disadvantaged geographical areas, supporting equal educational opportunities everywhere.

However, the rise of extended education in an augmented world also brings significant challenges (Srivastava, 2023). Ensuring equitable access to advanced technologies remains a central concern, as disparities in connectivity, digital literacy, and institutional capacity risk deepening existing inequalities (Makda, 2025). Ethical and pedagogical questions arise around data privacy, algorithmic bias, and the role of AI in shaping learning trajectories (Alam & Mohanty, 2023). Educators and learners must balance automation with human agency, preserving the social and emotional dimensions of learning while leveraging AI as a knowledgeable peer. The promise of extended education needs to follow technological innovation in putting in the centre a responsible approach.

This issue of Italian Journal of Educational Technology is devoted to extended education. The number of submissions received in response to the call for papers was so large that we were able to select 10 papers on this topic. Hence, Italian Journal of Educational Technology will devote two issues to this theme: the third of 2025 and the first of 2026.

Together, these issues will contribute to a better understanding of extended education in an augmented world. At the heart of the discussion, AI is one of the main drivers of the augmented world (Alasadi & Baiz, 2023). AI seems able to act as a catalyst for continuous education and personal growth. By analysing learners' evolving needs, AI systems can recommend tailored learning paths, identify emerging skill gaps, and adapt content dynamically to support career transitions or personal development. This integration of intelligent technologies extends learning beyond formal institutions, connecting professional training, informal learning, and self-directed study into a seamless continuum. These challenges are echoed in this special issue with a multidisciplinary approach to learning from Health Sciences to History passing through Engineering.

These special issues were conceived by an international and multidisciplinary team with people coming from Education science, Educational Technology and the development of the academic policy in terms of education and Lifelong Learning. As the development of the question of Extended Education is shared worldwide, it is a general concern of the team to have points of view on the topic coming from different parts of the world. Three of the editors are involved in the European Alliance UNITA. In order to get contributions from different countries, the Alliance UNITA was one of the main ways to reach contributors.

The selection of the contributions aimed to present a broad overview on extended education from different perspectives and disciplines. The contributors of this issue question the use of AI on education in particular on the writing with AI, on the retention of information with AI-generated multimedia, on a methodology question using Mayer's principles in multimedia learning (Mayer, 2021), the use of AI tool and contribution to support medical radiography training, and virtual artefacts on learning of structural engineering.

The issue is opened by Luca Botturi, Luca Cignetti and Silvia Demartini, exposing a study on the pros and cons of the use of AI on writing competences of the high school students in the Italian-speaking part of Switzerland. The study compares some of the features from Human-writing, mixed-approach between Human and AI and pure AI. One of the main points is to show the beneficial use of the AI needs to be framed by an appropriate teaching and learning approach. In other words, AI literacy is central for teachers and students to avoid an unquestioned use of the answer that the AI gives to the students.

The second contribution by Elisabetta Tombolini, Luna Lembo and Francesco Peluso Cassese points on the learning and information retention with AI-generated multimedia. As in the first contribution, the analysis reaches the conclusion on the need to integrate pedagogical frameworks and appropriate teaching methodologies and the improvement of digital literacy. The study involves Italian university students from different disciplines. Based on the research project AVENGERS: "Artificial Video for Education: New Generation Empowerment Resource for Study", the methodology follows two main concepts, Cognitive Theory of Multimedia Learning from Richard E. Mayer and Mobile Learning considering the development of mobile learning platforms. The study suggested that the retention of information based on AI-Multimedia can be improved by better training on the AI tools.

The third article by Melenia Talarico explores the integration of digital technologies in education using the principles of Richard E. Mayer. One of the main findings of the study is on the improvement of learning by the segmentation of educational scenarios. The question of interactivity is quite central in the discussion of the contributor. Positive, neutral and negative effects are analysed and show, by example, that the use of multimedia content in an immersive environment will be more engaging for students. Nevertheless, the need to develop learning modules with focus themes and materials is one of the keys to success in the integration of digital technologies for learners. As the previous papers, the contribution is underlining the success factors of the use of digital technologies. With this paper, the special issue focused on the basic principles of extended education: digital literacy of the teachers and the students. If this pre-condition is fulfilled, thus other points on the coherence and the meaning of the use in pedagogy need to be addressed in order to have the better use of AI tools supporting the students during their learning paths.

The fourth contribution by Ricardo Teresa Ribeiro, Lucas Mourot, Kevins Sprengers, Laurence Flaction, Claudio Sà dos Reis and Laura Elena Raileanu presents a study on the use of AI in the training of medical radiographers in Chest X-Ray Analysis. The platform introduces an innovative approach to medical imaging education. Results indicate positive perceptions of usability and learning outcomes, suggesting strong educational potential, though moderate trust and diagnostic performance ratings highlight scepticism towards AI reliability. Some limitations are pointed out by the contributors, in particular on the sample and on the long-term retention. Nevertheless, the next steps will require transparent communication, ethical awareness, and targeted training to integrate AI effectively into medical education.

The fifth contribution by Angela Spinelli and Gianluca Capurso relates the experiment made at the University of Rome Tor Vergata with students on the use of virtual reality and augmented reality on the teaching of History of Construction. Among the findings, they point to the fact that the experiment was more successful for mature students (last year of master's degree). The authors also raise the question of digital literacy, as some students report difficulties in using the AR and VR tools. As the first articles suggested in the theoretical framework, this case study suggests the need to introduce introductory modules or technical support at the beginning of the workshop or to include specific courses within the entire degree programme. Thus, high technical demands and time investment remain major challenges, highlighting the need for preparatory training in digital tools and better alignment with prior interdisciplinary knowledge. The authors suggest that future developments should focus on enhancing accessibility, teacher training, and formative evaluation systems, while exploring how scalable, customizable VR environments can be adapted to other disciplines to promote reflective, equitable, and interdisciplinary education.

These five articles demonstrate the potential for developing tools for extended education. They also point to the need to support the implementation of these tools by increasing the digital literacy of both teachers and students.

While this is reflected in the more theoretical articles rather than in the case studies, it is also clear that the question is not whether or not to use these tools. Indeed, the augmented world is a reality that is becoming increasingly prevalent in the educational environment. It is in this context that reading this special issue and the next is necessary in order to provide teachers, students and educational support services with the keys to taking into account the authors' main conclusions.

Acknowledgements

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Writing with, without and against the AI. Insights from a high school writing lab

Scrivere con, senza e contro l'IA. Cosa abbiamo imparato da un laboratorio di scrittura nella scuola media superiore

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ABSTRACT AI is enabling new practices to potentially extend education, but if such practices enhance or endanger learning is still under discussion. This study presents the findings of an explorative research conducted in a sophomore high school class in Italian-speaking Switzerland, aimed at investigating the impact of ChatGPT on fiction writing education. Students were provided with narrative stimuli and asked to write a short story on their own or with the support of ChatGPT 3.5. The resulting corpus was enriched with stories generated by ChatGPT alone. The analysis followed a dual quantitative and qualitative approach, examining the short stories in combination with feedback from authors and from a reading group composed of students of the same age. The results suggest clear differences among the three types of stories and a shift in focus during the writing process for students who used ChatGPT.

KEYWORDS ChatGPT; Creative Writing; Textual Analysis; High School.

SOMMARIO L'intelligenza artificiale rende possibili nuove pratiche educative, ma resta aperta la discussione su quanto tali pratiche migliorino o frenino l'apprendimento. Questo articolo espone i risultati di una ricerca esplorativa condotta in una classe del secondo anno di liceo nella Svizzera italiana, che ha esplorato l'impatto di ChatGPT sull'insegnamento della scrittura creativa. Dopo aver fornito stimoli creativi, agli studenti è stato chiesto di scrivere un racconto breve, individualmente oppure con il supporto di ChatGPT 3.5. Il corpus risultante è stato ampliato includendo anche testi generati esclusivamente da ChatGPT. L'analisi ha seguito un approccio misto, quantitativo e qualitativo, esaminando i racconti in relazione ai feedback degli autori e di un gruppo di lettura composto da coetanei. I risultati evidenziano differenze significative tra i racconti dei tre tipi, nonché un cambiamento di prospettiva nel processo di scrittura da parte degli studenti che si sono avvalsi del supporto di ChatGPT.

PAROLE CHIAVE ChatGPT; Scrittura Creativa; Analisi Testuale; Liceo.

1. Introduction

AI technologies have reached many domains of human activities. In particular, Generative Artificial Intelligence (GenAI, i.e., algorithms that generate new digital content like texts, images, video or audio files) and of Large Language Models (LLM, i.e., AI systems trained on vast amounts of text data to understand, generate, and manipulate human language) are changing many professional domains, including education. To harness their potential and control risks, re-thinking educational practices at all school levels is required, from homework (Ibrahim et al., 2023) to theses (Lopes, 2024) and from cheating (Lee et al., 2024) to plagiarism detection (Hutson, 2024). At its core, the challenge is reshaping educational contexts to help learners and teachers develop competences for living in an interconnected world populated by AI agents (Markauskaite et al., 2022).

LLMs are basically text-generation machines, and the concerns expressed above have a direct impact on the teaching and learning of writing skills. This paper reports an exploratory case study on the use of ChatGPT 3.5 for fiction writing in a high school class writing lab. Our purpose is twofold: on the one hand, exploring AI-assisted writing processes and experiences; on the other hand, identifying possible ways to exploit LLM-based tools to foster writing skills development.

2. State of the art

The writing process is deeply connected with human cognition and entails (or should entail) multiple phases and different skills, as shown since Flower and Hayes (1981), which go under the umbrella of "writing skills". Writing includes both authorial skills like identifying a context or situation in which the text makes sense, selecting content, organizing content, and choosing a style; and technical skills, like spelling, punctuation and grammar (Smith, 1983; 2013).

Writing is also a dynamic process that evolves in response to the development of the tools and the means through which it will be carried out. The Western contemporary society, which is deeply permeated by writing and by the widespread availability of increasingly sophisticated writing technologies, inevitably shapes both individual and educational writing practices (Williams & Beam, 2019). The recent large-scale accessibility of GenAI calls for a reconsideration of both writing opportunities and of the modalities through which writing is produced, for example in the form of assisted writing (a human author writes with the help of an agent) or delegated writing (a human delegates text production to an agent). Although published a few years ago, Sassoon (2019) provides relevant insights for the issue explored in our research. The study examines AI-driven storytelling in journalism, entertainment, and marketing, questioning its impact on authorship, originality, and reader engagement. It also addresses ethical concerns, including bias, authenticity, and the role of human creativity in an AI-mediated narrative discourse.

Human and AI interactions in writing, both in education and in the professions, is a new research domain in which multiple strands are being explored. One strand focuses on the quality of texts generated by GenAI-tools, often through comparison with texts by human authors, with controversial results (Sardinha, 2024; Gunser et al., 2022). Kindenberg (2024) conducted a comparative analysis between historical narratives generated by ChatGPT and those written by secondary school students, assessing both historical elements and narrative quality. He concluded that, while ChatGPT's narratives show better stylistic features, they lack the emotional depth present in human-generated narratives.

A second strand of research explores AI-supported writing, or the interactions of human authors with GenAI-tools in writing. Most research in this strand focuses on second language learning, and especially ESL (English as Second Language; Fahti & Rahimi, 2024; Song & Song, 2023). Ghajargar et al. (2022) investigate human-AI co-writing in fiction using GPT-3. Through two autoethnographic studies with varying narrative complexity, the authors examined the system's limitations and emergent capabilities, revealing its impact on creative practices and human-AI collaboration. Evidence so far clearly indicates that AI-assisted writing provides benefits in terms of quality of the textual output (at least for some text types), efficiency and motivation. On the other hand, in the context of writing education, the impact of GenAI-tool is still unclear (Abdullayeva & Musayeva, 2023). Whether the use of AI improves writing quality (i.e., the outcome text) or contributes to the actual development of students' writing skills is still under discussion (Daulay et al., 2024; Ironsi & Solomon Ironsi, 2024).

Research in this domain is of course still in progress, confronted with a technological landscape that is also undergoing rapid and in large part unpredictable evolution. New players are entering the market (e.g., the newcomer DeepSeek or Grok), and there is no consensus about the actual effectiveness of LLMs in different languages (Huang et al., 2023). While a few significant contributions are available, further investigations are necessary, especially for languages other than English like Italian.

In this study, we examine a classroom-based creative writing experience involving native Italian-speaking (L1) high school students, with and without the support of ChatGPT 3.5. The focus of our study is both on text quality, as perceived by human readers and through the results of textual analysis, and on the writing experience.

3. Methods

3.1. Research design

The study was conducted with a sophomore class attending a writing lab at a state high school in an urban area in Southern Switzerland. The vehicular language, and the language of writing, was Italian. Before the writing lab, all students already knew and used the free version of ChatGPT, even if with different frequencies and purposes. None of them had a pro subscription.

The 3-session writing lab was jointly facilitated by the Italian teacher of the class and the three authors of this paper. It was presented as a challenge: students would compete with ChatGPT in a mixed-mode fiction writing challenge. Writing fiction is a common topic in high school writing labs. Fiction writing fosters students' ability to shift perspectives and to construct, through imagination, alternative worlds (Lavinio, 1995; Cignetti, 2018; Cignetti et al., 2022). The experimentation workflow is illustrated in Figure 1.

The three sessions were organized as follows:

- *Session 1.* After a short introduction to LLMs, the challenge was presented. Each student received one of three writing stimuli, which consisted of a pair of cards from the *Work Kit Fiction Design* by NearFutureLab, portraying one object and one action (Figure 2), that had to be included in the short story; potential readers would be young people in their age group. Students were asked to develop an outline of the story focusing on the main character, a key challenge, and a resolution. They could then start writing a 5000-character fiction text in either mode: (a) asking ChatGPT to write the short story for them and then refining it, or (b) without the use of ChatGPT. The session was so designed, that at least two students for each stimulus wrote in each mode.
- *Session 2.* The second session was devoted to individual work for completing the story and submitting it. Students were then asked to fill in a Writer Questionnaire about their writing experi-

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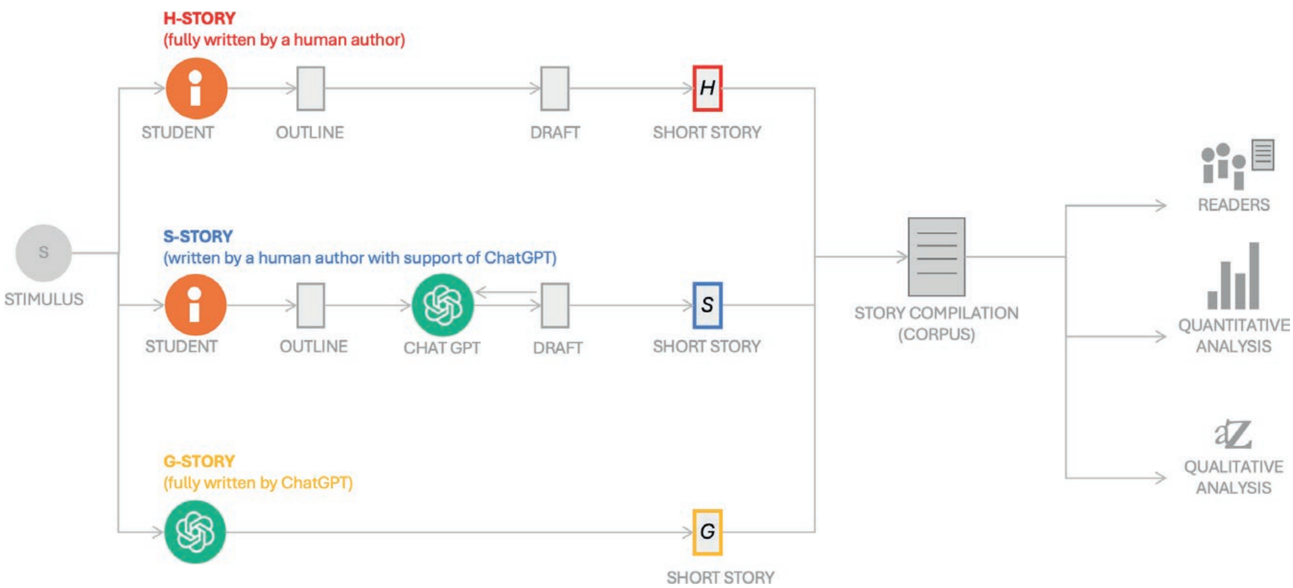

Figure 1. Experimentation workflow.

Figure 2. Sample writing stimulus.

ence during the lab (Table 1). The survey was independent from stimulus and writing mode and addressed focus and satisfaction; surveys could be paired with short stories through an alphanumeric code, so that anonymity by design was guaranteed. No personal data was collected.

– *Session 3.* In this session, students were handed out a compilation of all short stories. The compilation included three additional short stories generated by ChatGPT alone, using the prompt in Figure 3. Some were read aloud to the class for discussion. The researchers illustrated the results of the quantitative and qualitative analyses and discussed them with the students.

The class was composed of 13 students, but only 12 actually attended the lab and one did not submit the short story. The resulting short story corpus was composed of 14 short stories (Table 2).

ITALIAN

```
Scrivi un racconto di 2 facciate (circa 5000 battute). I tuoi
lettori sono ragazzi e ragazze tra i 15 e i 18 anni,
appassionati lettori.
Nel racconto devono essere presenti:
- l'oggetto STRUMENTO DA CUCINA (può comparire come un
  personaggio o come un altro elemento del racconto)
- l' azione RIUTILIZZARE.
Scegli liberamente l'ambientazione e lo stile narrativo.
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ENGLISH

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Write a story of two pages (approximately 5,000 characters).
Your readers are teenagers aged 15 to 18 who are passionate
about reading.
Your story must include:
The object KITCHEN TOOL (it can appear as a character or as
another element of the story).
The action REUSE.
You are free to choose the setting and narrative style.
```

Figure 3. The prompt used with ChatGPT for G-stories.

Table 1. Writer questionnaire.

Italian	English	Item type
Descrivi come hai lavorato per la scrittura del racconto	Describe how you worked on writing the story	Open answer
Qual è stata la cosa più difficile nella scrittura del racconto, o quella che ti ha chiesto più impegno?	What was the most difficult aspect of writing the story, or what required the most effort from you?	Open answer
Qual è la cosa di cui sei più soddisfatto/a del tuo racconto?	What are you most satisfied with in your story?	Open answer
Come valuti il tuo racconto?	How do you rate your story?	Likert scale [1-6]

Table 2. Short stories dataset (corpus).

N	Label	Description
6	H-stories	Short stories written by students without the use of ChatGPT
5	S-stories	Short stories written by students with the use of ChatGPT
3	G-stories	Short stories written completely by ChatGPT

3.2. Text assessment and analysis

The short story compilation was printed and 21 students of another sophomore class in the same school were assigned the reading and assessment of four short stories each. Assessment was formulated via an online Reader Questionnaire that captured their feedback in terms of perceived quality as readers, namely: overall quality, quality of writing, consistency, engagement, difficulty, imagination, originality, connection with reader's experience (Table 3). Also in this case, no personal data was collected.

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Table 3. Reader questionnaire.

Italian	English	Item type
Il racconto è coerente e non si contraddice	The story is coherent and does not contradict itself	Likert scale [1-5]
Il racconto è coinvolgente	The story is engaging	Likert scale [1-5]
Ci sono parti che non ho capito o non sono chiare	There are parts I did not understand or that are unclear	Likert scale [1-5]
Sono riuscito a immaginarmi luoghi, situazioni e personaggi del racconto	I was able to imagine the places, situations, and characters in the story	Likert scale [1-5]
Avevo già letto un racconto simile a questo	I had already read a story similar to this one	Likert scale [1-5]
Il racconto mette a tema qualcosa che è vicino alla mia esperienza	The story addresses something that relates to my experience	Likert scale [1-5]
L'autore/autrice di questo racconto sa scrivere bene	The author of this story writes well	Likert scale [1-5]
In generale, credo che sia un buon racconto	Overall, I think this is a good story	Likert scale [1-5]
Cosa ti è piaciuto di più di questo racconto?	What did you like most about this story?	Open answer
Secondo te, chi ha scritto questo racconto?	Who do you think wrote this story?	Open answer

The corpus was also analysed from a quantitative perspective. Although the number of texts was limited, we deemed methodologically appropriate to include this type of analysis in order to provide an overview of some significant features. The analysis was conducted using corrige.it[1] and READ-IT[2], and addressed: spelling accuracy and punctuation, syntactic complexity, readability index, and lexical features and quality (Table 4).

Table 4. Linguistic traits considered in quantitative analysis

Considered linguistic traits	Definition
Spelling Accuracy and Punctuation	The correct application of orthographic rules and the use of punctuation marks.
Syntactic Complexity	The structural elaboration of sentences in a text, typically measured through factors such as sentence length, clause embedding, and the use of diverse syntactic constructions.
Readability Index	A measure that evaluates the ease with which a text can be read, based primarily on linguistic factors such as sentence length and word complexity.
Lexical Features and Quality	The characteristics of vocabulary used in a text, including word frequency and diversity.

We selected these linguistic features because they are among those that can be analysed most efficiently using automatic tools. Moreover, such heterogeneous elements offer meaningful insights despite the limited size of the corpus and are relevant from a pedagogical perspective.

To complement the quantitative observations and explore more subtle aspects of textual quality, a qualitative analysis was conducted on selected excerpts from both G-stories and H-stories. The goal was to investigate features of writing that are less easily captured through automatic metrics but are crucial in assessing narrative sophistication, stylistic expressiveness, and authorial voice.

[1] https://pro.corrige.it/
[2] https://www.ilc.cnr.it/dylanlab/apps/texttools/

The selection of excerpts followed a purposive sampling strategy, aiming to identify representative passages that exhibited relevant linguistic, rhetorical, or narrative features. The analysis focused on surface-level linguistic patterns (e.g., unusual collocations, syntactic repetition), rhetorical structures (e.g., epiphora, emphasis), and deeper narrative components such as psychological plausibility and emotional framing.

4. Results

4.1. Authors' experiences

The writing experience of authors was analysed through the answers to the Writer Questionnaire (attachment 1). Authors of S-stories were more satisfied with their text than authors of H-stories (4.6 vs. 3.8 on a 5-point scale). Table 5 reports the elements that both groups of authors indicated as satisfying or challenging. Interestingly, authors of S-stories and H-stories emphasize almost completely different aspects, suggesting that, with the introduction of ChatGPT, the focus of the writing process had shifted: S-authors seem mostly concerned about interacting with the AI, and do not mention style consistency, character development and time management, which are frequently mentioned by H-authors.

Table 5. Satisfaction and challenge elements for authors

Authors	Satisfaction	Challenges
H-stories	Idea, plot, conclusion, writing process	Choosing words, describing characters, keeping a consistent style, time management.
S-stories	Idea, text smoothness, interaction with AI	Developing the outline, having the AI doing what I wanted, fine-tuning the text

4.2. Readers feedback

Readers' feedback was analysed through the Reader Questionnaire data. Given the limited number of participants, after confirming the absence of differences dependent on the original stimulus, only descriptive statistics was used.

When asked about writing and overall quality, young readers appreciated all three types of short stories, with a slight preference for S-stories. G-stories seem to have been less appreciated (Figure 4). Specific feedback items investigated text consistency, experienced engagement in the story, reading difficulty, imagination, originality, and connection with the reader's experience. Their scores are also rather balanced across H-, S- and G-stories, again with a slight preference for S-stories, especially when it comes to consistency and engagement (Figure 5). However, two remarkable differences emerge:

- H-stories are more difficult to read (H=2.31 vs. S=1.64, G=1,57)
- G-stories connect less with the reader's experience (G=1,61 vs. H=2.14, S=2.24).

Finally, readers were asked to guess who the author of each text was. Most readers of any type of short story identified the authors as "other boys/girls of our age" (about 60% of all answers). However, this choice is prevalent (about 75%) for G-stories. H-authors were more often identified as "writers", and S-authors were more often identified as "adults with other professions" (i.e., not writers). This might suggest that readers of H-stories perceived a stronger authorial voice.

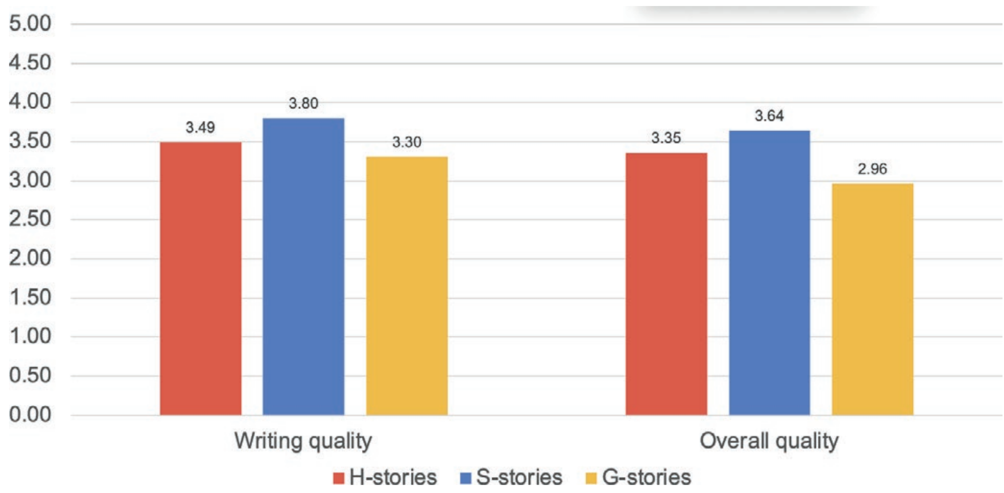

Figure 4. Quality assessment by readers.

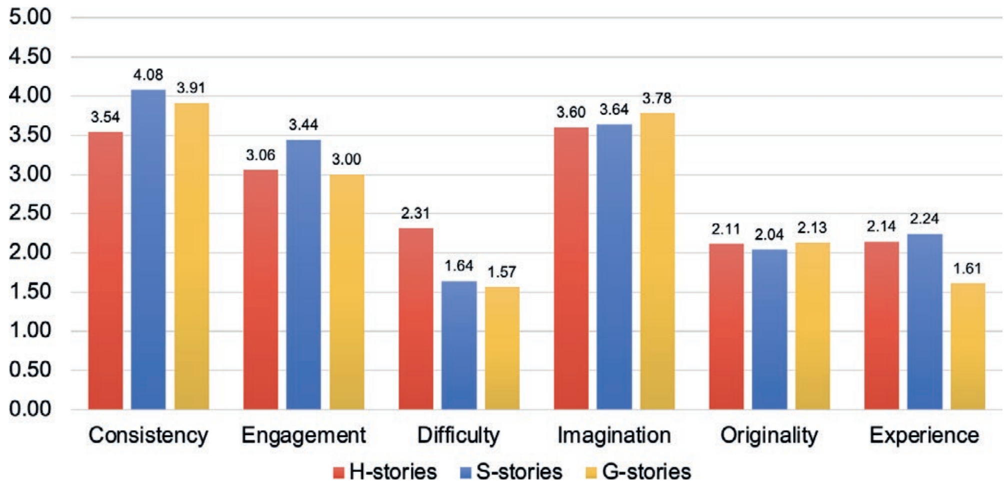

Figure 5. Detailed feedback by readers.

4.3. Quantitative text analysis

4.3.1. Spelling accuracy and punctuation

As expected, the texts generated by ChatGPT contain no spelling mistakes. In contrast, S-story texts contained two errors, while H-stories, which were written completely by students, presented a total of 13 mistakes, including missing accents and apostrophes, as well as missing commas in parenthetical elements. H-stories also presented additional morphological errors, e.g., plural-singular agreement mistakes like in “breve sequenze” (should be “brevi sequenze”) and “costanti e regolare esercizio fisico” (should be “costante e regolare esercizio fisico”).

While no quantitative analysis was conducted on punctuation, a general trend could be observed: ChatGPT exhibits a preference for standardized and repetitive solutions (sequences punctuated by full stops and commas), whereas human writers employ a wider range of strategies. Although their results may not always be entirely satisfactory, they are certainly more varied and effective in conveying the author's feelings and some particular stylistic effects. The following excerpt from an H-story starts with a nominal sentence, and the following paragraph includes a combination of period, comma and colon in order to emphasise the atmosphere of anxiety and tension in the text.

> ITALIAN
> Imprecazioni e preghiere. Queste erano le componenti distintive delle poche parole pronunciate in mezzo all'aria densa di paura e impazienza che sempre precedeva l'adrenalina innescata dal primo proiettile, dal rumore di eliche assassine: nel ventunesimo secolo i droni commerciali con cui gli appassionati di paesaggi naturali sorvolavano creste innevate in Ucraina trasportavano bombe da mortaio. [S3H]
> ENGLISH (translated)
> Curses and prayers. These were the distinctive components of the few words spoken amidst the thick air of fear and impatience that always preceded the adrenaline triggered by the first bullet, the sound of murderous propellers: in the twenty-first century, the commercial drones that nature enthusiasts used to fly over snow-covered ridges in Ukraine carried mortar bombs. [S3H]

Finally, in G-texts, the semicolon is not used at all; in contrast, it appears twice in S-stories and 13 times H-stories.

4.3.2. Syntactic Complexity

Syntactic complexity is a highly complex parameter. We present here some preliminary findings obtained through the automatic analysis tools mentioned above. First, average sentence length is higher in H-stories (20,37), slightly lower for S-stories (19,36) and about 25% lower for G-stories (15,37), which suggests that humans tend to use more words. This is likely to have contributed to the readers' impression that G-stories were easier to read.

In addition to this, through the READ-IT tool, we could observe the distribution of parts of speech and some specific structural preferences, including the frequency of coordination and subordination. Our findings indicate that human-written narratives tend to be more dynamic, showing a higher percentage of verbs (17,9%), used in a more varied way. This percentage decreases to 15,6% in the S-texts and further drops to 14,4% in those generated by artificial intelligence, which instead tend to favour nouns and adjectives.

Tables 6a and 6b provide an overview of the key aspects of the stories' syntactic profile: the percentage distribution of selected parts of speech (nouns, proper nouns, adjectives, verbs, coordinating and subordinating conjunctions; Table 6a), and the presence of coordinated and subordinated clauses (Table 6b). In addition to the previously mentioned features, the higher percentage of subordinate clauses is also a distinctive characteristic of H- and S-stories. This suggests a "human preference" for a more hypotactic structure in Italian-language writing.

4.3.3. Readability Index

The text analysis tool also allowed computing the readability index of the texts, namely GULPEASE, a standardized measure in linguistic studies specifically calibrated for Italian (Lucisano & Piemontese, 1988). GULPEASE provides indications about the relative "ease" or "difficulty" of a text in relation to the reader's educational level, considering word and sentence length. While these are not the only factors contributing to textual complexity, they offer an initial indication of readability, to combine with further lexical analysis. Corrige.it generates a text score between 1 (difficult) and 100 (easy).

Table 6a. Comparison of frequency of elements of the morpho-syntactic profile.

Part of speech	H-stories	S-stories	G-stories
Noun	18,4%	20,9%	20,8%
Proper name	2,7%	1,5%	3,3%
Verb	17,9%	15,6%	14,4%
Adjective	7,1%	8,6%	9,8%
Conjunction	4,9%	5%	4,5%
./. coordinating	*64,1%*	*68,1%*	*77,6%*
./. subordinating	*35,9%*	*31,9%*	*22,4%*
Main clauses	52,9%	57,5%	71,4%
Subordinate clauses	47,1%	42,4%	28,6%

Table 6b. Presence of main and subordinate clauses.

Kind of clause	H-stories	S-stories	G-stories
Main clauses	52,9%	57,5%	71,4%
Subordinate clauses	47,1%	42,4%	28,6%

The average scores of our subcorpora are as follows: H-stories 55, S-stories 54, G-stories 57. Overall, we observe no significant differences among the texts, which are generally very difficult for readers with primary or lower secondary education, but easily comprehensible for those with higher levels of education. However, some texts written by humans reach higher peaks of complexity (35). This is not inherently problematic, because in narrative texts complexity can be an interesting and appropriate feature, to be considered within the broader context of the author's stylistic choices.

4.3.4. Lexical Features and Quality

In general, H-stories show a slightly higher lexical richness; this measure refers to the range and variety of vocabulary deployed in a text. However, it is not possible to identify significant differences in this regard, as the measure obtained using Corrige.it ranges from 2,94 (H-stories) to 2,72 (S-stories) and 2,18 (G-stories).

Table 7. List of occurrences in the corpus (G stories were in general shorter)

H-stories	S-stories	G-stories
essere (163)	essere (107)	essere (30)
avere (77)	avere (45)	fonderia (14)
cavallo (34)	fabbrica (21)	Alvaro (13)
fare (28)	trovare (16)	antico (12)
Geremia (26)	Alex (15)	potere (11)
potere (24)	giorno (14)	fare (10)
Margaret (22)	tempo (14)	chiave (9)
mamma (21)	nuovo (13)	segreto (8)
ora (20)	fare (13)	biblioteca (8)
Zeno (18)	casa (13)	vecchio (7)

What is particularly interesting from a didactic perspective, however, is identifying the lexical preferences emerging in the different sub-corpora to examine the vocabulary of younger generations in written compositions. If, overall, more than 90% of the words belong to the Basic Vocabulary of Italian[3], lemmatization allowed us to obtain the lists of occurrences in Table 7.

The list highlights notable differences in the frequency of certain lemmas. For instance, the auxiliary verbs *essere* ("to be") and *avere* ("to have") appear with high frequency in H-stories but are underrepresented in G-stories. Similarly, the verb *fare* ("to do" / "to make") is used more frequently in H-stories and S-stories than in G-stories. One possible explanation is its occurrence in the first two groups within idiomatic expressions (*aveva fatto la sua parte* ["he/she had done their part"]; *poteva fare la differenza* ["he/she could make a difference"]) or in collocations (*vieni a fare colazione* ["come have breakfast"]), a pattern less evident in G-stories. It is also possible to observe the use of the verb *fare* as a generic verb (applicable in various phrasal contexts), a phenomenon that has been identified analysing a large corpus of handwritten texts produced at school in Canton Ticino (Cignetti et al. 2016), but further investigation is needed, along with a more precise balancing of the three sub-corpora. However, to formulate hypotheses about these frequency differences with a methodologically sound approach, the analysis should be extended to a larger number of texts and to different text types for a more comprehensive investigation.

4.4. Qualitative text analysis

4.4.1. Lexical choices

The qualitative analysis of the texts has revealed several noteworthy aspects. A primary linguistic feature concerns the use, in H-stories, of lexically possible choices that are uncommon in contemporary Italian usage. Examples of this phenomenon include the noun-adjective pair *mente vigilante* ("vigilant mind"), the phrase *destinata alla dimenticanza* ("destined for oblivion"; although attested in some literary texts of the past, is perceived in ChatGPT's usage as a marked shift in register), and specific noun pairs such as un *futuro fatto di reinvenzione e creatività* ("a future built on reinvention and creativity") and *un'oasi di storia e curiosità* ("an oasis of history and curiosity").

ITALIAN
[1] Ogni giorno, con occhi penetranti e MENTE VIGILANTE, sorvegliava la biblioteca e il potere che essa racchiudeva. [S2G1]
[2] La vecchia frusta, una volta DESTINATA ALLA DIMENTICANZA, aveva trovato una nuova vita e una nuova bellezza. [S1G1]
[3] E mentre la notte scendeva sulla tranquilla cittadina di San Giorgio, il loro portacandele illuminava il cammino verso UN FUTURO FATTO DI REINVENZIONE E CREATIVITÀ. [S1G1]
[4] Nella pittoresca cittadina di San Giorgio, la bottega di antiquariato "La Stamberga delle Meraviglie" si stagliava contro il panorama urbano, UN'OASI DI STORIA E CURIOSITÀ. [S1G1]

ENGLISH (translated)
[1] Every day, with piercing eyes and a VIGILANT MIND, he watched over the library and the power it contained. [S2G1]

[3] https://www.dropbox.com/scl/fi/zg2y99xqik4k11nj19fgi/nuovovocabolariodibase.pdf?rlkey=s0uf8ggv11kf44ip6a2ldz16n&dl=0

[2] The old whip, once DESTINED FOR OBLIVION, had found a new life and a renewed beauty. [S1G1]
[3] And as night fell over the quiet town of San Giorgio, their candle holder illuminated the path toward A FUTURE BUILT ON REINVENTION AND CREATIVITY. [S1G1]
[4] In the picturesque town of San Giorgio, the antique shop "The Wonders' Attic" stood out against the urban landscape, AN OASIS OF HISTORY AND CURIOSITY. [S1G1]

4.4.2. Lexical repetitions

Anaphoric chains in texts generated by ChatGPT frequently rely on lexical repetition, even in contexts where the use of pronouns or synonyms would render the text more natural and effective. This is evident in the repetition of the noun *fonderia* ("foundry") in the following example from a G-story:

ITALIAN
[5] Un giorno, durante una passeggiata solitaria, Alvaro notò un'inconsueta attività intorno alla FONDERIA. Uomini e donne dall'aspetto losco si aggiravano furtivamente, portando con sé strani attrezzi e materiali misteriosi. Deciso a scoprire cosa stesse accadendo, Alvaro si avventurò oltre il cancello arrugginito della FONDERIA, conscio del pericolo che lo attendeva. Una volta dentro, Alvaro rimase sbalordito. La FONDERIA non era più l'antica officina abbandonata che credeva. [S3G1]

ENGLISH (translated)
[5] One day, during a solitary walk, Alvaro noticed an unusual activity around the FOUNDRY. Men and women with a suspicious appearance lurked furtively, carrying strange tools and mysterious materials. Determined to uncover what was happening, Alvaro ventured beyond the rusty gate of the FOUNDRY, fully aware of the danger that awaited him. Once inside, Alvaro was astonished. The FOUNDRY was no longer the abandoned old workshop he had believed it to be. [S3G1]

Lexical repetitions also occur in texts written by humans; however, in such cases, their rhetorical-expressive function is evident. The repetition of *stanco* ("tired") in the following H-story excerpt demonstrates a deliberate and expressively effective use of the rhetorical figure known as *epiphora*, emphasizing the phrasing:

ITALIAN
[6] Geremia era molto STANCO. Ogni lunedì arrivava a casa STANCO. Ogni giorno che andava a scuola tornava STANCO. Ma il lunedì era peggio. A Geremia piaceva la scuola ma il lunedì era faticoso. Soprattutto se sei un bambino di 10 anni e vedi tuo padre solo il fine settimana. [S1H2]

ENGLISH (translated)
[6] Geremia was very TIRED. Every Monday, he came home TIRED. Every day he went to school, he returned TIRED. But Mondays were worse. Geremia liked school, but Mondays were exhausting. Especially if you are a ten-year-old child and see your father only on weekends. [S1H2]

4.4.3. Character development, narrative development and causality

Another aspect that emerged from the qualitative analysis – undoubtedly deserving of further investigation in a future study – is the absence of affective and emotional factors related to the protagonists in G-stories. By contrast, such factors appear especially in H-stories, where they enrich the psychological portrayal of the character and can even serve as key elements in the narrative development of the story, as demonstrated by examples 7 and 8. Another emerging pattern in the qualitative analysis concerns the use of causality. G-stories often display a linear but shallow causal structure, where events follow each other with limited elaboration on motivations or consequences. This results in narratives that are formally coherent but semantically weak in terms of depth and psychological realism. By contrast, H-stories frequently construct causal relationships between actions and emotional or contextual elements. Consider the example in 7, where the character's decision to leave home is clearly motivated by emotional turmoil, adding plausibility and engagement to the storyline. This richer causal connectivity appears linked to the human author's greater awareness of psychological plausibility and narrative logic.

ITALIAN
[7] Preso DALL'IRA E DAL DOLORE, il ragazzino corse in camera sua e preparò lo zaino pronto a partire verso quella maledetta fabbrica. Ora più che mai era convinto di voler andare e DIMENTICARE DEL SUO CARO CANE, non poteva convivere anche con QUEL DOLORE… ne aveva passate già abbastanza. [S3H1]
[8] Così uscì di casa silenziosamente ARRABBIATO E ADDOLORATO, SENZA NEANCHE LANCIARE UN ULTIMO SGUARDO A SUA MAMMA, che non si era ancora mossa. NON PROVAVA NEMMENO A PREOCCUPARSI DI LUI. [S3H1]

ENGLISH (translated)
[7] Overcome with RAGE AND PAIN, the boy ran to his room and packed his backpack, ready to head toward that cursed factory. Now more than ever, he was determined to go and FORGET ABOUT HIS BELOVED DOG; he could not bear THAT PAIN as well… he had already endured too much. [S3H1]
[8] Thus, he left the house silently, ANGRY AND HEARTBROKEN, WITHOUT EVEN CASTING ONE LAST GLANCE AT HIS MOTHER, who had not yet moved. SHE DIDN'T EVEN SEEM TO WORRY ABOUT HIM. [S3H1]

5. Discussion

The small-scale experimentation presented in this study was localized in a specific high school context, involving a small sample, a specific language (namely, Italian), a specific genre (fiction short story), and a particular chatbot (ChatGPT 3.5). Moreover, the research design only considers a specific way of using GenAI-tool in writing (namely, in generating the first draft of the text). For these reasons, its results cannot be generalized, especially to learning scenarios that include other ways of using AI in writing (e.g., for generating ideas, or improving specific passages, etc.) or different tools. Nonetheless, the results help shedding some light both on the textual quality that can be expected from GenAI-tools and on the impact of such tools in the writing process and in writing education.

The data collected from the Writer Questionnaire clearly indicated that for the authors of S-stories, the focus of writing was the interaction with ChatGPT, and not writing itself. It can be argued that such a shift in focus is more conducive to the development of AI Literacy skills (how do I interact effectively with a chatbot?) than of actual writing skills (e.g., developing an own writing style). However, the balance between the two could be fine-tuned by providing appropriate tasks and scaffolding learners at different stages.

Both Readers Questionnaire results and the text analyses indicated that stories generated by ChatGPT were error-free and easier to read, e.g., they had shorter sentences, less lexical variety, used less verbs and more nouns, and included more repetitions. While these textual features can be adapted with proper prompting, they suggest that AI-generated texts can be used as models of writing only to a limited extent, and only in relation to specific features. ChatGPT writing style tends to follow standard plain writing rules.

However, the qualitative text analysis revealed deeper insights into the nature of human vs. AI-generated writing. First, lexical choices in H-stories revealed a greater stylistic variety and a deliberate use of marked or literary expressions, contributing to a richer textual fabric. These expressions were virtually absent in G-stories, where vocabulary tended to be more standardized. This signals a lower lexical experimentation in AI-generated texts, potentially limiting students' exposure to more expressive or nuanced language.

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Secondly, lexical repetition was employed differently across the two text types. While ChatGPT-generated stories frequently repeated nouns mechanically, human writers used repetition rhetorically and expressively, for example through epiphora (as in the repeated use of *stanco*). This finding emphasizes how repetition, when human-driven, contributes to rhythm and emotional emphasis, whereas in G-stories, it often results from limitations in co-reference management.

A third important distinction regards character development, where H-stories incorporated affective and emotional states that shaped the protagonists' decisions and narrative progression. Emotions such as anger, sorrow, and frustration are not only described but causally linked to plot events, as seen in examples. G-stories, in contrast, tended to lack emotional depth and internal perspective.

Such observations suggest that writing without AI provides more opportunities to develop authorial skills, exactly because the overall focus remains on writing as such and is not shifted to interacting with a machine or partner. We also interpret these results as a call to continue the conversation about the artistic value of AI-generated artefacts (Kraaijeveld, 2024).

6. Conclusions

The key results of this small-scale exploratory study were also presented and discussed with the participants and their teacher. The framework of a "challenge with AI" proved to be an effective motivational element for engaging in writing, and the whole process provided several opportunities to discuss not only writing, but also how LLM work and our individual and societal relationship with AI, in the framework of AI Literacy education (Ranieri et al., 2023). These are also venues that deserve further exploration.

This study explored student's use of AI in writing, ignoring the obviously detrimental situation in which students fully hand over writing to the AI. Our results support the idea that AI can be beneficial for learning to write, as AI-generated texts indeed possess relevant features, e.g., they are easier to read and use shorter sentences. However, our participants' experience suggests that AI can be beneficial to writing education only if framed within an appropriate teaching and learning approach. New AI-supported instructional strategies should be developed, to prevent the focus shifting from writing to use an AI tool that students reported. Such strategies might identify more contextualized and task-oriented modes of integration of Gen-AI tools into specific phases in the writing process. Following are some examples:

- Conversating with a chatbot to generate useful ideas (for fiction) or arguments (for argumentative texts) before developing the outline of a text.
- Enhancing lexical choices by expanding the generic vocabulary frequently used by students encouraging them to find more precise alternatives using AI support, critically reflecting on contextual appropriateness and on pragmatic effects.
- Interacting with a chatbot for *revising* drafts (as opposed to *generating* drafts), using a prompt that asks the system not to simply "improve the text", rather to "highlight passages that can be improved and suggest possible improvements", until a satisfactory result is achieved. Then, the various versions produced (by different people) can be compared and discussed.

These examples limit the use of AI to specific writing phases (e.g., *inventio*, or *elocutio*), so that students get feedback that they should elaborate. In this way, the output of the GenAI tool is never the final target text, leaving the main agency to the student. Implementing such interactions requires a high level of control on the writing process, which might be difficult to achieve for younger students. Such interactions might also be embedded in a game-like situation like "continue each other's story" (Yang et al., 2022).

More generally, our results suggest that integrating AI in teaching and learning processes requires a careful analysis of learning processes – in our case, the writing process. Using AI to enhance education is not just a matter of generating higher-quality products (e.g., texts) or making the process more efficient (e.g., spend less time writing longer texts). Learning requires time and effort, and AI can be easily used as a shortcutting that does not necessarily imply better learning (Bohacek, 2023). To generate meaningful integration of AI in teaching and learning situations, both teachers' and students' basic AI Literacy is required in order to avoid a "magic approach", in which Gen-AI tools are considered like omniscient oracles or humanized.

From a research point of view, it would certainly be valuable to replicate the study in at least three directions: (a) expanding the sample size and varying its composition, e.g., controlling for writing skills or habits; (b) including different text types, for enriching and strengthening the analyses with also with e.g., descriptive, normative or argumentative texts; and (c) using different Gen-AI tools. We also expect that the comparison of similar studies across different languages would generate insights in how LLMs generate language and interact with human writers.

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8. Attachments

8.1. Attachment 2. Short story assessment

Original Italian version

- Il racconto è coerente e non si contraddice [Likert scale 1-5]
- Il racconto è coinvolgente [Likert scale 1-5]
- Ci sono parti che non ho capito o non sono chiare [Likert scale 1-5]
- Sono riuscito a immaginarmi luoghi, situazioni e personaggi del racconto [Likert scale 1-5]
- Avevo già letto un racconto simile a questo [Likert scale 1-5]
- Il racconto mette a tema qualcosa che è vicino alla mia esperienza [Likert scale 1-5]
- L'autore/autrice di questo racconto sa scrivere bene [Likert scale 1-5]
- In generale, credo che sia un buon racconto [Likert scale 1-5]

- Cosa ti è piaciuto di più di questo racconto? [open answer]
- Secondo te, chi ha scritto questo racconto? Ad esempio, un ragazzo, una ragazza, uno scrittore di professione, una giornalista, uno scienziato, ecc. [open answer]

Translated English version

- The story is coherent and does not contradict itself. [Likert scale 1-5]
- The story is engaging. [Likert scale 1-5]
- There are parts I did not understand or that are unclear. [Likert scale 1-5]
- I was able to imagine the places, situations, and characters in the story. [Likert scale 1-5]
- I had already read a story similar to this one. [Likert scale 1-5]
- The story addresses something that relates to my experience. [Likert scale 1-5]
- The author of this story writes well. [Likert scale 1-5]
- Overall, I think this is a good story. [Likert scale 1-5]
- What did you like most about this story? [open answer]
- Who do you think wrote this story? For example, a boy, a girl, a professional writer, a journalist, a scientist, etc. [open answer]

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The impact of AI-generated multimedia on learning and information retention

L'impatto dei contenuti multimediali generati dall'IA sull'apprendimento e sulla ritenzione delle informazioni

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ABSTRACT Generative Artificial Intelligence (GAI) is transforming education, offering new opportunities for the creation of innovative teaching tools that facilitate access to content. This study, conducted within the framework of the AVENGERS project – *Artificial Video for Education: New Generation Empowerment Resource for Study* – involved 66 university students and aimed to evaluate the effectiveness of a GAI-generated video based on a text excerpt from the AMOS psychometric test, designed to assess comprehension, organisation, and memory skills. The objective was to compare the impact of multimedia presentation with that of traditional textual delivery. The findings suggest that educational videos generated using GAI can enhance memory retention, but are less effective in supporting the sequencing of concepts. GAI thus emerges as a promising resource for learning support, but it needs to be integrated into a broader pedagogical framework and complemented by active teaching methodologies in order to maximise its effectiveness.

KEYWORDS Higher Education Learning; Generative Artificial Intelligence (GAI); Multimedia Learning; Cognitive Performance; Learning Enhancement.

SOMMARIO L'Intelligenza Artificiale Generativa (IAG) sta trasformando l'istruzione, offrendo nuove opportunità per la creazione di strumenti didattici innovativi che facilitano l'accesso ai contenuti. Questo studio, condotto nell'ambito del progetto *AVENGERS - Artificial Video for Education: New Generation Empowerment Resource for Study*, ha coinvolto 66 studenti universitari, per valutare l'efficacia di un video generato con IAG basato su un testo tratto dal test AMOS, volto a misurare abilità di comprensione, organizzazione e memorizzazione delle informazioni. L'obiettivo era confrontare l'impatto della presentazione in formato multimediale rispetto alla tradizionale fruizione testuale. I risultati suggeriscono che i video didattici generati con IAG possono migliorare la memorizzazione, ma risultano meno efficaci nel favorire la sequenziazione dei concetti. L'IAG emerge, dunque, come una risorsa promettente per il supporto all'apprendimento, ma necessita di essere inserita in una progettazione pedagogica più ampia e affiancata da metodologie didattiche attive per massimizzarne l'efficacia.

PAROLE CHIAVE Apprendimento Universitario; Intelligenza Artificiale Generativa (IAG); Apprendimento Multimediale; Prestazione Cognitiva; Miglioramento dell'Apprendimento.

1. Introduction

The AVENGERS: Artificial Video for Education: New Generation Empowerment Resource for Study research project, presented in this paper, is set within a broader educational landscape undergoing profound transformation. This shift is characterised by the increasingly pervasive integration of advanced technologies such as Generative Artificial Intelligence (GAI). This evolution presents unprecedented opportunities to personalise learning, automate teaching support, and innovate the creation of educational content. However, the adoption of GAI in education also raises critical concerns regarding the reliability of information, data protection, and algorithmic transparency, as highlighted by Altares-López et al. (2024).

Today's students predominantly belong to Generation Z and Generation Alpha, groups that have grown up immersed in digital technologies, which have strongly influenced their learning and communication habits. Although these generations demonstrate a natural familiarity with connected devices, online platforms, and artificial intelligence tools—used both for entertainment and for accessing educational resources—numerous recent studies indicate that such exposure does not automatically translate into advanced digital competence (Creighton, 2018; Ferrari, 2012; Kassim et al., 2020; Ziatdinov & Cilliers, 2022). In other words, even if members of these generations are technologically adept, this does not necessarily imply that they possess the critical skills to select, interpret, and evaluate information effectively, nor advanced abilities in digital problem solving or in the pedagogically meaningful production of multimedia content (Blayone, 2018). This perspective moves beyond the deterministic view tied to the notion of "digital natives" (Prensky, 2009), instead emphasising the importance of intentionally and systematically developing digital competence.

This discrepancy between technological exposure and critical digital competence raises questions about how educational institutions should structure their teaching methodologies. Research in the field of pedagogy suggests that technology integration in education must be guided by targeted strategies, promoting meaningful and conscious learning rather than passive consumption of digital tools (Limone, 2020). In this context, the development of innovative teaching methodologies that leverage technology effectively to enhance teaching and learning processes becomes essential.

Several educational approaches have sought to address this need. The SAMR model (Substitution, Augmentation, Modification, Redefinition), proposed by Puentedura (2006), suggests that technology should not merely replace traditional methodologies (e.g., replacing textbooks with PDFs) but should also modify and redefine the learning experience, introducing new forms of interaction and collaboration between students and teachers (Zamri et al., 2024).

The TPACK framework (Technological Pedagogical Content Knowledge), on the other hand, emphasises the necessity of adequate teacher training to enable effective integration of technology into instructional design (Mishra & Koehler, 2006).

Another major challenge is the increasing use of Artificial Intelligence (AI) tools in education, which provide unprecedented learning support opportunities but also require a high level of digital literacy and critical thinking skills for responsible use (Hinojo-Lucena et al., 2019). Generative AI, for example, can be employed to customise learning pathways, provide automatic feedback, and create interactive educational materials. However, it also raises concerns regarding the reliability of generated information and the risk of excessive dependence on automated tools.

With the advent of Generative Artificial Intelligence (GAI), the concept of multimedia learning has further evolved. Platforms based on GAI, such as Pictory.ai, Synthesia, and DeepBrain, enable the creation of personalised educational content, adapting it in real time to students' needs. This approach not only enhances engagement but also supports adaptive learning, allowing students to receive explanations tailored to their level of comprehension (Luckin et al., 2016).

One of the most promising applications of GAI in education is the ability to automatically generate videos, combining speech synthesis, explanatory images, and interactive animations. According to recent studies, these tools can increase motivation and information retention, particularly among students with learning difficulties (Berg et al., 2024). However, it is crucial to ensure that the content generated is accurate and pedagogically valid, thus avoiding the risk of disseminating misleading or erroneous information (Kasneci et al., 2023).

Furthermore, it is essential to consider the ethical and pedagogical implications of integrating GAI into education. As discussed by Altares-López et al. (2024), the adoption of GAI requires careful reflection to ensure that these technologies are used responsibly and contribute effectively to enhancing educational processes.

Given these considerations, there is a pressing need to rethink teaching methodologies, ensuring that they not only exploit the potential of new technologies but also enable students to develop a critical and strategic use of digital tools. This would enhance the quality of learning and better prepare students for the demands of the modern workforce (Christine, 2017).

In this context, GAI offers the possibility of creating personalised teaching materials, such as educational videos that integrate audio narration with relevant visual elements. These tools facilitate deeper understanding and a more engaging learning experience, as highlighted by Mello et al. (2023).

This research aims to explore the impact of GAI in the design of multimedia teaching tools, assessing their effectiveness in enhancing information acquisition. By leveraging advanced GAI platforms, innovative educational content will be developed with the goal of providing students with autonomous resources that support study and enrich the learning experience.

In conclusion, GAI represents a promising frontier for educational innovation. However, its implementation must be accompanied by careful consideration of students' digital competencies and appropriate teaching methodologies to maximise benefits and mitigate potential risks.

2. Theoretical Framework

The AVENGERS research project is grounded in a robust theoretical framework based on two fundamental concepts: the Cognitive Theory of Multimedia Learning and Mobile Learning.

The Cognitive Theory of Multimedia Learning, developed by Richard E. Mayer (2001), is an essential theoretical model for understanding how the integration of words and images can positively influence learning processes. According to this theory, the simultaneous presentation of information through visual and auditory channels enhances comprehension and retention by leveraging the human cognitive system's ability to process these two input modes separately (Mayer, 2001; Mayer et al., 2008). Mayer's central hypothesis suggests that the coherent organisation of multimedia elements fosters deeper and more lasting knowledge construction while reducing the risk of cognitive overload (Sweller, 1988; 1993).

The application of multimedia learning principles in educational settings has led to the development of instructional strategies that optimise the use of audiovisual materials. Mayer identified several design principles aimed at improving learning effectiveness. Among these, the coherence principle suggests removing non-essential elements to avoid distractions, while the segmentation principle highlights the importance of breaking content into manageable units to facilitate cognitive processing (Mayer, 2005). The Modality Principle, introduced by Mayer and Moreno (2003), states that students learn more effectively when information is presented through images accompanied by audio narration rather than written text. This approach optimises cognitive processing by utilising separate channels for visual and auditory information. Presenting verbal information through audio narration prevents visual channel overload, enabling a more balanced cognitive load distribution and facilitating both comprehension and retention.

Mayer and Moreno further demonstrated that the combined use of images and audio narration enables students to construct more coherent and integrated mental representations. This occurs because audio narration frees up cognitive resources that would otherwise be occupied with reading, allowing for greater focus on image processing and its integration with verbal information. Consequently, students develop stronger connections between different representations of information, ultimately enhancing learning outcomes.

Mobile Learning (m-learning) has introduced a significant transformation in the educational landscape, leveraging the portability, connectivity, and interactivity of mobile devices to expand learning opportunities (Hockly, 2013). With the widespread adoption of smartphones and tablets, students can now access digital educational resources in real time and from any location, thereby overcoming traditional spatial and temporal constraints imposed by conventional education (Criollo et al., 2021; Goundar et al., 2022). This learning model promotes greater flexibility and personalisation, allowing adaptation to individual cognitive styles and learning paces and fostering ubiquitous learning, in which education is no longer confined to a physical classroom but extends to diverse real-world contexts (Di Fuccio et al., 2022; Limone, 2020).

The progressive integration of mobile educational platforms, interactive applications, and artificial intelligence has further enhanced the learning experience, enabling the development of adaptive and personalised learning environments.

While m-learning offers significant advantages in terms of accessibility and personalisation, several challenges must be addressed. These include the availability of digital infrastructure, the quality of educational content, and teacher training to effectively integrate these technologies into instructional programmes (Sophonhiranrak, 2021). Recent studies suggest that the success of m-learning depends not only on the technology itself but also on effective pedagogical design, which combines interactive strategies, collaborative learning, and continuous assessment tools to maximise educational benefits (Naveed et al., 2023).

The integration of the Cognitive Theory of Multimedia Learning with Mobile Learning presents a promising synergy for educational innovation. The segmentation of content into short, manageable modules aligns well with the needs of students using mobile devices, fostering a more dynamic and scalable learning approach (Gupta et al., 2021). Furthermore, the incorporation of interactive multimedia elements in m-learning increases student engagement, encouraging more active and immersive learning experiences (Fiorella et al., 2021; Goundar et al., 2021).

To ensure the effectiveness of these methodologies, it is crucial that the design of instructional materials is grounded in scientifically validated principles and considers the specific characteristics of mobile devices, such as smaller screen sizes and different interaction modes (Crompton et al., 2018).

The adoption of multimedia strategies and mobile technologies not only improves teaching quality but also provides students with a more flexible and personalised learning experience, making them active participants in their educational journey. In this context, research on the interaction between multimedia learning and m-learning continues to evolve, presenting new challenges and opportunities for the future of education.

2.1. Generative Artificial Intelligence in Education

Generative Artificial Intelligence (GAI) is emerging as a transformative force in the educational sector, offering unprecedented opportunities to personalise learning, automate instructional support, and innovate content creation (Mao et al., 2024). This advanced technology can autonomously generate texts, images, and sounds, opening new possibilities for teaching and learning.

GAI allows for the development of tailored educational materials that meet the specific needs of each student. By analysing learning data, it can design personalised educational pathways, offering explanations and resources aligned with learners' levels of understanding and interests (Alasadi et al., 2023). This approach aims to enhance learning effectiveness by fostering greater motivation and active participation (Altares-López et al., 2024).

The integration of GAI-powered chatbots and virtual assistants offers students immediate support, answering questions, clarifying doubts, and providing real-time feedback. These tools can reduce the workload of teachers, allowing them to focus on more strategic aspects of teaching. However, it is essential to ensure that the responses generated are accurate and pedagogically sound, to avoid the spread of misleading or incorrect information (Łodzikowski et al., 2024).

At the same time, numerous studies have highlighted the limitations and risks associated with the use of GAI in education, including concerns about the reliability of generated content, dependency on automated systems, the diminishing role of teachers, and issues related to data privacy and algorithmic transparency (Kasneci et al., 2023; Tzirides et al., 2024).

Recent Italian pedagogical literature has also begun to critically explore these issues. Limone (2020) stresses the importance of integrating digital technologies through intentional pedagogical planning rather than adopting them for their own sake. Calvani (2021) synthesises empirical evidence on the effectiveness of educational technologies, advocating for a reflective and evidence-based approach. In this context, Di Padova and Lotti (2024) propose a pedagogical model focused on inclusive education, in which GAI is used in service of accessibility and participation, grounded in sound educational principles.

GAI also facilitates the creation of interactive multimedia content such as educational videos, simulations, and personalised quizzes. These tools can help explain complex topics in more accessible and engaging ways, fostering deeper understanding. Moreover, GAI can continuously update learning materials based on the latest findings and trends, ensuring that content remains relevant (Tzirides et al., 2023).

In summary, while GAI holds transformative potential for education, its integration must be critically and responsibly approached, taking into account not only its benefits but also its ethical, pedagogical, and cultural implications. Only through a thoughtful, evidence-informed, and context-sensitive use can GAI truly enhance teaching and learning processes.

2.1.1. GAI: Pictory.ai for Didactics

Generative Artificial Intelligence (GAI) is transforming the educational sector through advanced tools that automate and personalise the creation of multimedia content. Among the emerging platforms, Pictory.ai[1] stands out as an innovative AI-based tool designed to rapidly and efficiently convert written texts into narrative videos. This technology has the potential to revolutionise teaching by providing visual and auditory support that enhances students' learning experiences, particularly in the context of Mobile Learning (m-learning) and Multimedia Learning (Mayer, 2021).

[1] Pictory. Pictory – Home of AI Video Editing Technology — pictory.ai. https://pictory.ai/. [Accessed 17-May-2023].

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Pictory.ai utilises artificial intelligence to analyse and interpret a text, automatically generating a visual storyboard incorporating images, video clips, and synthetic narration. The application of this tool in education aligns with several principles of Mayer's Cognitive Theory of Multimedia Learning (2001), particularly the Modality Principle, which asserts that combining images with audio narration is more effective than reading a text accompanied by static images (Mayer & Moreno, 2003). Additionally, the Segmenting Principle applies to Pictory.ai, as the platform breaks content into logical and sequential fragments, facilitating comprehension and reducing students' cognitive load (Sweller, 1988).

The integration of Pictory.ai into educational contexts can be particularly beneficial in addressing diverse learning styles and cognitive preferences. The creation of customised visual content enables more immediate access to information, increasing student engagement and motivation to learn (Tzirides et al., 2023). Furthermore, AI-generated videos enhance learning personalisation, allowing teachers to adapt instructional materials to the individual needs of students, thereby improving teaching effectiveness (Altares-López et al., 2024).

The adoption of platforms such as Pictory.ai represents a significant step towards the digitalisation of education, making instructional materials more accessible, interactive, and engaging. While Generative Artificial Intelligence provides innovative tools for educational content creation, a critical and reflective approach is essential to ensure a positive impact on student learning and future teaching methodologies.

2.2. The impact of educational videos on cognitive processing and semantic memory

The introduction of technology into education has led to the development of new educational resources, including instructional videos, which facilitate learning by combining visual and auditory stimuli, significantly modulating working memory and promoting more effective semantic memory retention. Compared to text-based instruction alone, videos enable the association of new concepts with dynamic imagery, enhancing the ability to construct semantic connections within the neural network and integrate information into existing knowledge structures (Mayer, 2020; Bonaiuti, 2013).

Video-based learning is grounded in deep processing mechanisms, where semantic encoding plays a crucial role in meaning construction. The combined use of images and narration facilitates information organisation, enabling students to create coherent cognitive structures that support long-term retrieval (Santos Espino et al., 2020). Additionally, the ability to review and segment content strengthens memory consolidation, facilitating the transition of information from working memory to long-term memory (Sweller, 2011). The visual presentation of materials, particularly through animations, auditory production, and graphic representations, helps to overcome the challenges of purely verbal memory, making concepts more accessible and enduring (Mayer & Moreno, 2003).

Another fundamental aspect is the flexibility of asynchronous learning, which allows students to self-regulate their processing times, repeating complex sections while accelerating simpler ones. This process enhances semantic encoding, as it enables students to focus on essential details and actively integrate new material with prior knowledge (Noetel et al., 2021; Mitra et al., 2010). Furthermore, videos foster active engagement through practical demonstrations and simulations, which stimulate deeper cognitive processing, essential for the retention of complex concepts (Zu et al., 2017).

The use of instructional videos thus represents a powerful tool for managing cognitive load, promoting more effective information processing, and facilitating access to a more stable and enduring semantic memory. The combination of visual and verbal stimuli, along with the ability to customise the learning pace, provides students with an optimal strategy for acquiring, organising, and consolidating information, ultimately enhancing comprehension and retention of content (Carmichael et al., 2018; Kanellopoulou et al., 2019).

3. Research project

The research project AVENGERS – Artificial Video for Education: New Generation Empowerment Resource for Study explores the impact of Generative Artificial Intelligence (GAI) on the learning process of university students. Specifically, it aims to assess how the use of automatically generated multimedia educational materials may influence the ability to organise information and memorise and recall content, compared to more traditional presentation formats.

3.1. Research Hypothesis

In the present study, the research hypotheses are as follows:

- H1: the use of multimedia material generated through Generative Artificial Intelligence (GAI) influences university students' ability to identify and sequence the fundamental content of a text.
- H2: the use of multimedia material generated through Generative Artificial Intelligence (GAI) influences university students' memorisation and recall of information contained in a text.

3.2. Sample

The research sample consists of 66 participants, including 40 females and 26 males, aged between 21 and 35 years. All participants are of Italian nationality and originate primarily from central Italy. The sample comprises university students enrolled in various academic programmes at different Italian universities, with a distribution of 60% in the humanities and 40% in the scientific field. Specifically, the disciplines represented include medical biotechnology, economics, engineering, philosophy, psychology, and sports sciences.

Recruitment was conducted on a voluntary basis through announcements disseminated via academic and social channels. Participation in the study did not involve any form of financial compensation. To ensure the suitability of participants and the validity of the collected data, specific inclusion and exclusion criteria were established.

The inclusion criteria required: (1) adequate proficiency in the Italian language, considered essential for understanding and processing the experimental materials; (2) a minimum educational qualification equivalent to a secondary school diploma; (3) enrolment in a university degree programme; (4) an age of 18 years or older. The exclusion criteria included: (1) a diagnosis of Learning Disorders (LD), which was self-reported and confirmed through a preliminary screening; (2) the presence of sensory impairments (visual or auditory) that could compromise the ability to engage with the experimental multimedia content; (3) the presence of cognitive deficits, potentially affecting comprehension and memory performance in the experimental tasks; (4) prior knowledge or familiarity with the psychometric instrument used, to avoid biases related to test familiarity.

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3.3. Tools and Methods

The present study employed the AMOS battery – Abilities and Motivation for Study: Assessment and Guidance Tests for Upper Secondary School and University (De Beni et al., 2014), focusing specifically on the first subtest of the Learning Test (PA). This subtest is an integral component of the AMOS battery and was selected to assess university students' abilities in comprehension, processing, memorisation, and recall of information.

The subtest used in this research involves the study of a passage entitled *"The Protohistory of Africa"*, which is part of the standard material provided by the AMOS battery. The text is designed to simulate typical academic content and requires participants to analyse its thematic structure and memorise key information. It is important to highlight that the content is unrelated to topics usually covered in school or university curricula, thereby reducing the risk of advantages due to prior knowledge and ensuring optimal conditions for assessing cognitive performance. The passage includes descriptive information, numerical data, conceptual elements, and prompts for reflection.

The research design followed the standard procedure for administering the Learning Test from the AMOS battery, with the distinction that the passage was presented in the form of a multimedia video generated via Generative Artificial Intelligence (GAI). The video was produced using the Pictory.ai platform, which, based on an input text, generated a multimedia narrative by combining explanatory images, video clips, and synthetic narration, while also displaying the written text. Participants were therefore presented with the same material used in the psychometric assessment, but in a different format (Figure 1).

The experiment was conducted between January and February 2025 in a controlled laboratory setting, with the constant presence of the researcher to ensure compliance with experimental conditions.

The research design adhered to the traditional protocol for administering the Learning Test from the AMOS battery. Before participating in the experiment, all participants signed an informed consent form in accordance with ethical guidelines for scientific research. Data processing was conducted in full compliance with current privacy and data protection regulations, ensuring complete anonymisation of collected information.

Figure 1. Screenshot of the video generated with GAI.

Participants were instructed to study the material according to their usual habits, without additional guidance, to avoid influencing spontaneous learning strategies. A 25-minute period was allocated for independent study, during which students could manage the video freely - pausing it, watching it twice in succession, or rewinding it. Following the study phase, a 30-minute break was scheduled, during which participants could engage in other activities. This pause between the study phase and the knowledge assessment was introduced based on experimental evidence suggesting that an interval of 15-30 minutes is sufficient to estimate the long-term retention of study material, with results comparable to those obtained in assessments conducted the following day (De Beni et al., 2014).

After the interval, participants proceeded with the content acquisition assessment. To this end, they completed two tasks designed to obtain objective measures of processing and recall abilities, with a maximum time limit of 8 minutes per task.

The first task, employed to test Hypothesis H1, required participants to select, from 14 titles, the seven key elements needed to construct a summary outline of the text's essential content, useful for an oral presentation. The seven unselected titles acted as distractors: although relevant to the topic, they did not represent the core conceptual elements. This task allowed for an assessment of planning abilities, specifically the ability to identify key concepts, organise them chronologically according to the text's narrative structure, and create a logical and functional sequence for subsequent oral exposition.

The second task, employed to test Hypothesis H2, consisted of a true/false questionnaire designed to assess the memorisation of specific information. To this end, 40 statements were created, of which 19 were true, corresponding to content present in the passage and only slightly paraphrased, and 21 were false, formulated in a plausible manner but not contained in the original text.

Statistical data analysis was conducted using JAMOVI software (version 2.3.28). To assess whether the scores obtained at the tests "Choice and Order of Events" ($\mu = 13.71$) and "True/False Questions" ($\mu = 24.72$) differed statistically significantly from the normative values established for university students in the standardised psychometric test AMOS, a two-tailed one-sample z-test was conducted for each variable.

3.4. Data analysis & results

Table 1 presents the descriptive statistics for the two tasks, "Choice and Order of Events" and "True/False Questions", designed to test whether the use of multimedia material generated through Generative Artificial Intelligence (GAI) influences university students' abilities to identify and sequence the core concepts of a narrative (H1) and to memorise and recall specific studied information (H2).

Table 1. Descriptive Statistics.

	N	Missing	Mean	Median	SD	Minimum	Maximum
Choice and order of events	66	0	13.68	14.00	2.22	9	18
True/false questions	66	0	30.73	30.00	4.94	24	43

To provide a graphical representation of the data distribution, violin box plots are reported in Figure 2 and Figure 3. The score distribution for the "Choice and Order of Events" task (Figure 2) appears

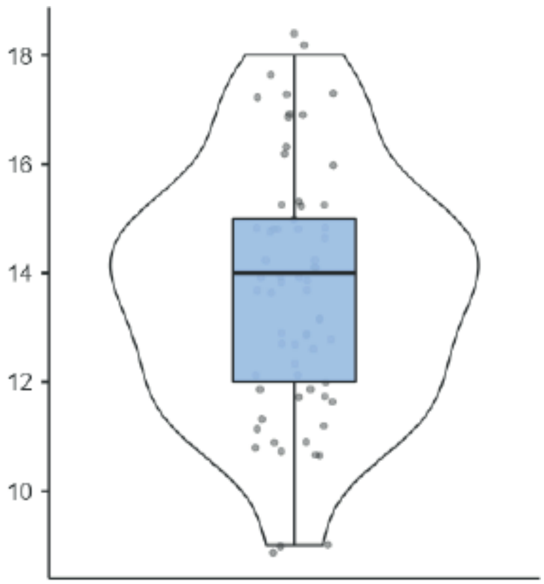

Figure 2. Box plot for Task 1 (H1).

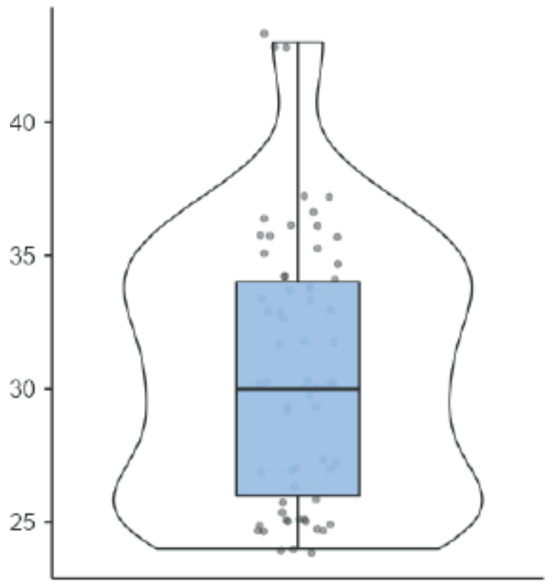

Figure 3. Box plot for Task 2 (H2).

approximately symmetrical. The violin shape suggests a moderate concentration of data around the median, with no evident outliers. Conversely, the distribution of scores in the "True/False Questions" task (Figure 3) exhibits greater variability, with a slight asymmetry and an extended upper tail, indicating that some participants obtained significantly higher scores than the mean.

To determine whether the sample means significantly differed from the normative values of the reference population, two-tailed one-sample z-tests were conducted for each research hypothesis.

For the "Choice and Order of Events" task, related to H1, a two-tailed one-sample z-test with α = 0.05 was conducted to compare the sample mean (M = 13.68, SD = 2.22) with the normative population mean (μ = 13.71, σ = 2.98). The results (Table 2) indicated no statistically significant difference between the sample and the population (z = -0.08, p = .935, d = -0.01). Consequently, H1 cannot be confirmed, and the null hypothesis was retained: the experimental intervention did not influence the ability to identify and sequence the core concepts of a narrative within the sample.

Table 2. H1 one-sample z-test.

Observed z	Standard Error	p	Effect Size
-0.08	0.37	0.935	-0.01

Conversely, for the "True/False Questions" task, related to H2, a two-tailed z-test with α = 0.05 was conducted to compare the sample mean (M = 30.73, SD = 4.94) with the normative population mean (μ = 24.72, σ = 4.95). The results (Table 3) revealed a statistically significant difference between the sample and the population (z = 9.86, p < .001,), with a very large effect size, according to Cohen's d (d = 1.21). Therefore, H2 is confirmed, and the null hypothesis was rejected: the experimental intervention had a significant impact on the ability to memorise and recall specific studied information within the sample.

Table 3. H2 one-sample z-test.

Observed z	Standard Error	p	Effect Size
9.86	0.61	< .001	1.21

In summary, regarding the ability to identify and organise the key concepts of a text (the "Choice and Order of Events" task), the results suggest that watching the GAI-generated video did not have a significant impact on students' ability to structure information in a sequential and coherent manner, at least when compared to the standard textual format used in the AMOS test.

By contrast, the findings for the memorisation and recall of specific information (the "True/False Questions" task) indicate that the GAI-generated video enhanced information retention, likely due to the communicative redundancy provided by the simultaneous integration of text, images, and audio.

4. Discussion

In recent years, Generative Artificial Intelligence (GAI) has transformed the educational landscape, offering new opportunities for the creation of innovative and personalised instructional content (Altares-López et al., 2024; Kasneci et al., 2023). The integration of GAI into teaching is part of a broader digital transformation in education, in which modalities such as multimedia learning (Mayer, 2020) and mobile learning (Hockly, 2013) are redefining how knowledge is accessed.

According to the Cognitive Theory of Multimedia Learning, the combined use of images, audio narration, and text can enhance comprehension and information retention by activating multiple sensory channels, which reduce cognitive load and facilitate more effective processing (Mayer & Moreno, 2003; Sweller, 2011). Simultaneously, Mobile Learning (m-learning) has made learning more flexible and accessible, allowing students to engage with educational resources anytime and anywhere (Criollo et al., 2021).

Recent studies highlight that AI-generated educational videos, such as those produced by Pictory.ai, can enhance motivation and information retention, particularly among students with learning difficulties (Berg et al., 2024). However, in order to determine whether these technologies genuinely improve learning processes, it is necessary to analyse which cognitive mechanisms are activated and what pedagogical implications they entail.

Based on these considerations, the present study aimed to investigate whether the exposure to narrative multimedia content generated using Pictory.ai (which employs GAI), integrating explanatory images, video clips, and synthetic narration while also maintaining the written text, influenced university students' ability to identify and organise the key concepts of a text (H1) and their memory retention and delayed recall of information (H2).

The findings provide insights into the potential and limitations of GAI in university-level learning. Statistical analysis revealed that, while H1 was not confirmed, H2 found support in the data. In other words, the experimental instructional tool did not significantly improve students' ability to identify and organise key information compared to traditional teaching materials. However, it had a positive effect on their ability to memorise and recall specific details related to the studied content.

This discrepancy can be explained by considering the cognitive processes involved in the two tasks. AI-generated videos appear to facilitate semantic memory, as they present information through multiple sensory channels (visual, auditory, textual), which enhances processing and reduces cognitive load (Sweller, 2011). This effect aligns with previous research indicating that specific details are more effectively consolidated when the material is structured to minimise cognitive effort by leveraging dual coding theory (Mayer, 2020; Santos Espino et al., 2020).

However, the use of the experimental instructional support did not lead to an improvement in active information processing and conceptual organisation skills. Structuring information coherently requires deeper cognitive processing (Kasneci et al., 2023). While memory retention can benefit from stimulus redundancy and automated processing, conceptual organisation necessitates more active interaction with the content, such as constructing concept maps (Sweller, 2011).

Thus, the findings suggest that GAI, when used to create multimedia learning tools, should ideally be complemented by active learning methodologies to maximise its educational benefits.

4.1. Limitations and future directions

This study presents some limitations that should be taken into account when interpreting the results. First, the sample consisted exclusively of Italian university students, which limits the generalisability of the findings to other educational contexts. Future studies could expand the sample to include students of different age groups and cultural backgrounds.

Several studies have shown that multimedia materials may be particularly beneficial for students with learning disorders or cognitive difficulties, offering visual and auditory support that facilitates access to content (Berg et al., 2024). Further investigation in this direction could contribute to the development of innovative and inclusive educational tools tailored to the needs of a diverse student population. Additionally, future research could assess, through longitudinal studies, the long-term retention of knowledge acquired through AI-generated educational resources.

Another important limitation concerns the lack of a direct comparison between AI-generated videos and those produced by human instructors. Although this study has shown that AI-generated videos can support information retention, it has not evaluated whether these outcomes are due to specific features of AI-generated content (e.g., neutrality, uniformity, scalability) or simply to the effectiveness of the multimedia format itself. Future research could explore this aspect further, also taking into account the absence of studies in the literature using the AMOS battery in combination with videos produced by human instructors.

5. Conclusion

Generative Artificial Intelligence (GAI) is emerging as an innovative resource in the educational field, offering unprecedented opportunities to support teaching through the automatic creation of personalised multimedia content. Thanks to its capacity to integrate text, images, and audio in a synergistic way, GAI enables the development of accessible and engaging materials that facilitate access to instructional content and enrich students' learning experiences.

The findings of the present study contribute to expanding the existing literature on the actual potential and limitations of GAI in educational contexts. The data collected suggest that educational videos generated using GAI-based technologies, such as Pictory.ai, may serve as effective tools for enhancing memory retention and recall, due to communicative redundancy and the stimulation of multiple sensory channels. However, the lack of a significant impact on students' ability to conceptually organise information highlights a critical issue: although multimedia formats may effectively support mnemonic retention, they do not automatically lead to the development of higher-order cognitive skills such as logical structuring and deep understanding of content. This discrepancy underscores the importance of viewing GAI not as a stand-alone or self-sufficient solution, but rather as a tool to be integrated within an intentional instructional design that includes active learning methodologies and pedagogical strategies aimed at fostering critical thinking, metacognitive reflection, and conscious engagement with content.

Looking ahead, it is essential to promote a critical, context-sensitive, and pedagogically grounded use of GAI, one that takes into account the characteristics of the learners, the educational objectives, and the specific learning environments. Further research could more thoroughly investigate the role of GAI in relation to different learner profiles, disciplinary domains, and the interaction between AI-generated content and the active role of the teacher in the instructional process. In this regard, it will be important to distinguish the effectiveness attributable to the specific characteristics of artificial intelligence from that related, more generally, to the multimedia format employed.

In light of these considerations, the use of GAI in education should not be confined to content generation alone, but rather incorporated into a broader pedagogical framework that combines technological innovation with evidence-based teaching methodologies. Only through such an approach can the full potential of GAI be realised, ensuring more effective, critical, and meaningful learning experiences.

6. Author contributions

The contribution represents the result of a collaborative effort by the authors; specifically, Elisabetta Tombolini is the author of §§ 3, 4, 5; Luna Lembo is the author of 1, 2; Francesco Peluso Cassese is research supervisor.

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Evaluating immersive digital environments through Mayer's principles of multimedia learning

Valutare gli ambienti digitali immersivi mediante i principi della multimedialità di Mayer

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ABSTRACT In recent years, integrating digital technologies in education has fostered the development of immersive and interactive learning environments. This study analyzes digital products made by students in the Technologies of Instruction and Learning course at the University of Turin evaluating them according to Mayer's principles of multimedia. The analysis showed significant results concerning segmentation principles, spatial contiguity, and Interactivity, while personalization and coherence have room for improvement. Results on correlations between variables indicate that appropriate visual and structural design improves the learning experience by reducing redundancy and cognitive overload. The 'balance between multimedia, interactivity, and segmentation is essential to ensure effective learning. The educational implications highlight the need for pedagogic design to maximize the potential of new educational technologies.

KEYWORDS Multimedia; Augmented Learning; Augmented Reality; Gamification; 3D Models.

SOMMARIO Negli ultimi anni, l'integrazione delle tecnologie digitali nella didattica ha favorito lo sviluppo di ambienti di apprendimento immersivi e interattivi. Questo studio analizza i prodotti digitali realizzati dagli studenti del corso di Tecnologie dell'istruzione e dell'apprendimento presso l'Università di Torino valutandoli secondo i principi della multimedialità di Mayer. L'analisi ha evidenziato un ampio rispetto dei principi di segmentazione, contiguità spaziale e interattività, mentre la personalizzazione e la coerenza presentano margini di miglioramento. Le correlazioni tra variabili indicano che un'adeguata progettazione visiva e strutturale migliora l'esperienza didattica, riducendo la ridondanza e il sovraccarico cognitivo. I risultati suggeriscono che un equilibrio tra multimedialità, interattività e segmentazione è essenziale per garantire un apprendimento efficace. Le implicazioni didattiche evidenziano la necessità di una progettazione pedagogicamente solida per massimizzare il potenziale delle nuove tecnologie educative.

PAROLE CHIAVE Multimedialità; Didattica Aumentata; Realtà Aumentata; Gamification; Modelli 3D.

Introduction

In recent years, there has been a significant increase in innovative teaching methodologies, especially in the educational and academic fields. The concept of augmented learning is becoming increasingly prominent, thanks to the possibility of creating highly flexible and adaptable digital learning environments. These methodologies are not new, and technological advances have made educational solutions more flexible and accessible, enabling the development of personalized and inclusive learning paths for students at all levels (Bonaiuti, 2017; Bruschi, 2021). Among the emerging technologies that are changing the educational landscape, augmented reality and 3D objects have attracted some interest. Among the emerging technologies transforming the educational landscape, augmented reality and 3D objects play a leading role. The presence of advanced three-dimensional modeling software and the widespread availability of 3D printers has enabled the integration of these tools into teaching and learning processes (Roopa et al.,2021; Qosimov et al., 2022). Interest in such solutions is related to five key factors:

– Content accessibility and usability enable intuitive and barrier-free use of digital materials.
– Integration into learning environments makes these tools easy to incorporate into immersive teaching platforms.
– The visual impact, manipulation, and representation of concepts in three dimensions overcome traditional two-dimensional representation's limitations and foster deeper understanding.
– Engagement and retention of attention and increased student motivation occur through active interaction with digital objects.
– Contextualization of learning, allowing 3D content to be visualized in real environments, placing them in meaningful scenarios rather than abstract contexts.

While physical models are sufficient to support learning (Yammine & Violato, 2016), digital technologies offer deeper exploration.

For example, 3D visualization makes it possible to analyze the internal structure of the human ear, explore complex anatomical details, and, most importantly, simulate scientific phenomena that are difficult to replay in reality.

These developments fit into a broader perspective of inclusive and augmented learning, concepts gaining increasing relevance in contemporary educational research (Familoni & Onyebuchi, 2024).

Integrating 3D objects and immersive methodologies finds significant applications in STEM disciplines (Science, Technology, Engineering, and Mathematics) and medicine (Moro et al., 2021; Yamazaki et al., 2023), where the manipulation of three-dimensional models strengthens theoretical understanding through practical experiences (Hidayat & Wardat, 2024).

The literature highlights several experiences conducted in educational settings from elementary school to university. It emphasizes the potential of these tools to create immersive and engaging learning environments for students (Geana et al., 2024). (Ibáñez, & Delgado-Kloos, 2018; Roffi & Cuomo, 2022). A crucial aspect, however, concerns the pedagogical design of these technologies. While students appreciate using advanced digital tools, integrating various multimedia formats into an immersive environment can be problematic. The increasing diffusion of virtual tours (Özdemir & Dag, 2022), augmented reality, interactive videos, and gamification calls for a critical reflection on the effects of these tools within the framework of New Media Education, mainly because these contents can be accessed on various devices, including mobile devices (Lisana & Suciadi, 2021). As evidenced in their systematic review, Çeken and Taşkın (2022) point out that the majority of existing studies concentrate on the analysis of instructional activities within conventional learning contexts, whereas significantly fewer investigations have explored the potential of virtual or augmented reality, or more broadly, immersive learning environments. Starting from this perspective, the research has explored the following question: What aspects do students focus on when designing an augmented lesson where they must integrate multiple linguistic codes into an immersive environment?

The initial hypothesis is that a digital environment, when paired with a well-structured instructional design, promotes a better balance of media content.

To answer the question, an analysis was conducted on the projects created by students enrolled in the primary education sciences degree program at the University of Turin, using Mayer's principles of multimedia learning (2005) as evaluation criteria, which will be further explored in the following chapters.

2. Augmented reality and 3D object

Today, the adoption of immersive and augmented reality (AR) technologies is radically changing the teaching of disciplines, offering new opportunities to improve student engagement and learning. AR simulations and three-dimensional environments actively help students understand complex concepts, making content more accessible and interactive (Abdinejad et al., 2021; Avci et al., 2019). These technologies help overcome the limitations of traditional teaching, providing students with a more immersive experience that stimulates active learning, fosters greater engagement (Garzón, 2021; Hidayat & Wardat, 2024), and develops creativity (Yousef, 2021).

Numerous studies have highlighted the educational potential of virtual reality in STEM education, demonstrating how interaction with three-dimensional models and dynamic simulations can significantly improve conceptual understanding and the acquisition of practical skills (Pellas et al., 2017). Exploring interactive digital environments, manipulating virtual objects, and participating in simulated experiments enables students to develop an experimental approach and refine their problem-solving skills (Tzima et al., 2019). Research widely documents the effectiveness of immersive technologies in teaching specific disciplines such as chemistry and anatomy, where visualizing molecular structures or anatomical models in 3D improves comprehension and information retention significantly.

Similarly, using augmented reality in scientific education has positively impacted learning abilities, enhancing student-content interaction through more immersive educational experiences. These studies confirm that immersive technologies and augmented reality represent innovative teaching tools capable of enriching STEM and other disciplines while improving the learning experience through increased Interactivity and student engagement (Szymkowiak et al., 2021). However, for these technologies to be truly effective, their integration into teaching must be appropriately structured and based on solid scientific evidence (Haleem et al., 2022).

3. Multimediality

Multimedia, cognitive load management, and gamification are fundamental to designing effective digital learning environments. Integrating text, images, videos, and 3D models allows for a diversified presentation of information, improving comprehension and content retention. When well-designed, multimedia reduces the risk of cognitive overload, promoting more effective information processing by students. Recent studies show that the combined use of videos and augmented reality enhances engagement and knowledge retention compared to traditional text-based methods (Geana et al., 2024; Gómez-Rios et al., 2022). Hattie's (2008) meta-analysis has long confirmed the effectiveness of student-centered teaching methods in learning.

At the same time, content segmentation plays a crucial role in decreasing cognitive load and optimizing learning processes.

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Cognitive load theory suggests that dividing material into smaller modules facilitates information processing, positively affecting comprehension and attention (Sweller, 2010).

Mobile technologies and augmented learning enable more flexible and adaptive access to educational content, reflecting this approach (Criollo- C et al., 2021).

Research highlights that integrating interactive and multimedia methodologies within a structured environment enhances learning effectiveness.

This effect is strongest when educators harmonize visual and textual elements to avoid Redundancy and facilitate a more intuitive experience (Sansone & Ritella, 2020).

Another key element that supports learning is gamification, which applies game mechanics (points, challenges, levels, rewards) to educational contexts.

Recent studies show that gamification boosts student motivation, enhances their learning experience, and encourages active participation (Kao et al., 2023). This approach becomes particularly effective when combined with multimedia elements and segmentation strategies.

It breaks content into interactive and engaging activities, reducing the risk of cognitive overload (Khaldi et al., 2023). Gamification has also proven especially useful in e-learning environments, where integrating game dynamics helps maintain student attention and engagement (Zeybek & Saygı, 2023). In summary, multimedia enhances learning by structuring information clearly and accessibly, balancing different communication formats, and using segmentation strategies to facilitate cognitive processing. Gamification transforms learning into a more dynamic and engaging process, increasing motivation and improving knowledge acquisition.

4. The education field

The Instructional Technologies and Learning course, which is part of the Primary Education Sciences curriculum at the University of Turin, aims primarily to provide second-year students with conceptual and methodological elements related to technologies in the educational field. One of the course's sub-objectives is to train students in designing learning environments and being able to choose the principles and methods for online teaching. In 2024, students created augmented teaching lessons as a requirement for passing the final exam, producing approximately 100 augmented lessons in total. The professor asked students and non-attendees to create a micro-lesson on a specific topic, incorporating multimedia elements such as a 3D object. The work was done individually on a topic chosen and agreed upon with the course instructor. The lesson design followed two phases. First, we ask students to complete the following grid (Table 1).

In the second phase, students were asked to implement the design grid using a free program called Thinglink. This program allows the creation of virtual and digital environments that are not exclusively educational but suitable for such purposes. For assessment, each product could be awarded between zero and five points, which could be added to the final exam score, with a maximum of 26/30 points. Below is the reference table with the evaluation criteria (Table 2).

In the next paragraph, we will analyze the reference sample.

4.1. The sample

One hundred project sheets and 100 digital products created by primary education students were collected. As previously described, the digital products were required to feature:

Table 1. Project grid.

Target	Characteristics of the participants
Aims	The learning goals
Discipline	For example, subjects such as history, science, Italian, and related disciplines.
Topic	For example, Egypt or the Roman Empire
Description of the context	Formal or non-formal context. Is the activity carried out at school or in an extracurricular setting?
Setting	How is the space organized?
Times	What are the design timelines?
Description of the activity:	Describe the multimedia elements that characterize the activity (objects, images, videos, etc.)
Work phases and reference methodologies	In which teaching moment does the activity take place? What methods are employed?
Technologies	App, Software
Expected results	What knowledge or skills are expected to be acquired?

Table 2. Evaluation grid.

Criteria	Description	Score
1. A 3D object (downloadable from Sketchfab.com)	Students were required to identify a 3D model relevant to the lesson content on the Sketchfab platform. The 3D model can be accessed using mobile devices and, in some cases, projected using augmented reality.	1
2. At least one textual description of the content	Students were required to insert one or more textual descriptions related to the theme addressed, coherent with other elements. They were asked not to insert a referential lesson description but to add important content-related information.	0,5
3. At least one image and one explanatory video	Using the ThingLink platform, students are required to select either a 2D or a 360-degree image to begin their work. Subsequently, they were asked to include at least one 2D image or a video as content within their project.	0,5
4. At least one game related to the contents	Students were asked to balance gamification principles learned during the lesson with educational content.	1
5. Educational value, not just entertainment value	This included creating game environments, balancing educational elements with entertainment, and paying attention to cognitive overload. Students were expected to design clear and coherent content aligned with the educational design principles in the project grid.	2

1. A background: a 2D or 360-degree image that had to be consistent with the referenced lesson. The option to choose the background was influenced by the difficulty of finding 360-degree images through search engines (see Fig. 1 and 2).
   As illustrated in Figure 3, 2D images account for a higher proportion (68%) compared to 360-degree images (32%). This distribution aligns with the instructional design objectives, which emphasized the development of an augmented learning activity, with a particular focus on augmented reality. Nevertheless, the inclusion—albeit less frequent—of 360-degree images indicates an exploratory use of more immersive environments, thereby extending the learning experience toward the affordances of virtual reality.

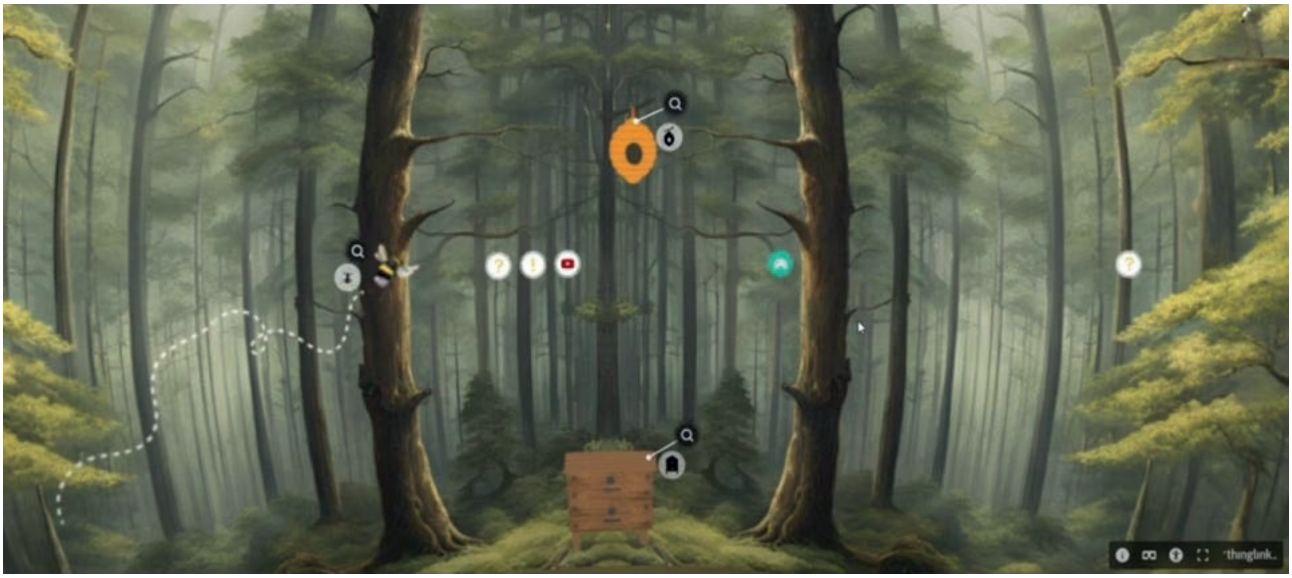

Figure 1. 360-degree Image within the ThingLink environment. Image created by Thinglink's artificial intelligence.

Figure 2. 2D Image within the ThingLink environment created by Canva.

2. A 3D object is consistent with the educational objectives and provides added value to the lesson. In this case, 3D objects were also selected through the Sketchfab website. The 3D objects had to be clear, high-resolution, and relevant to one of the lesson topics (see Figure 4).

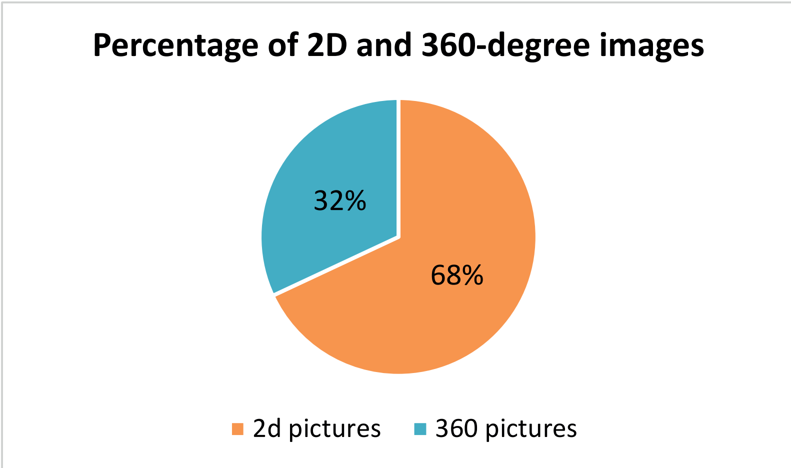

Figure 3. Percentage of 2D and 360 degrees images.

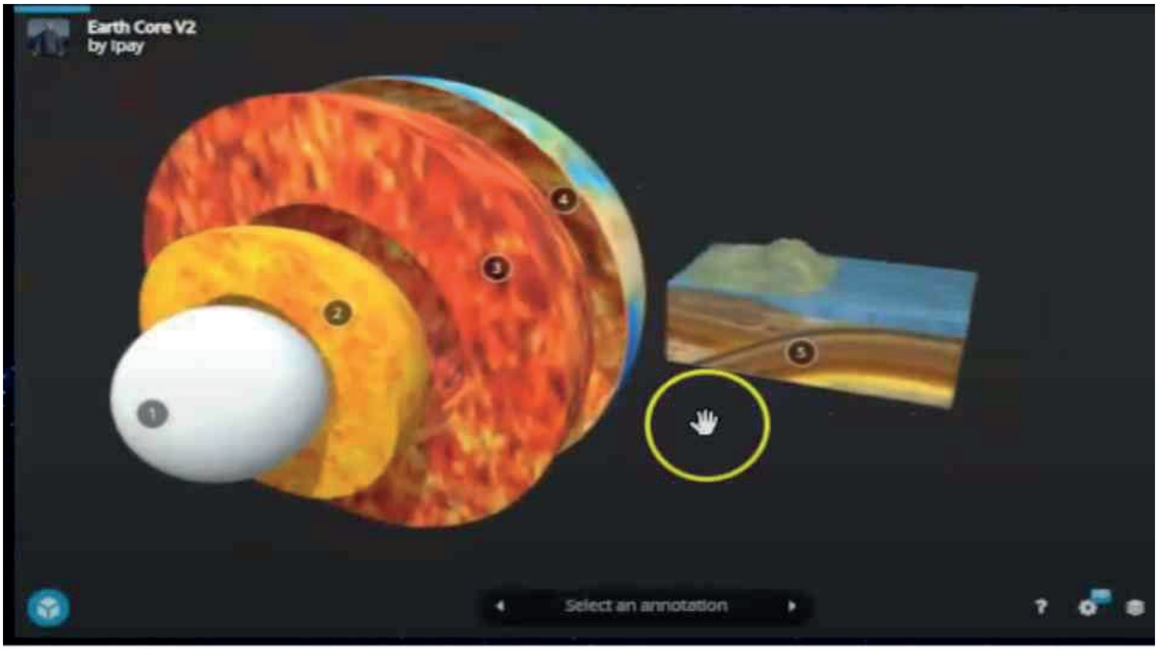

Figure 4. The 3D object of the Earth's layers. Image of Ipay from Sketchfab.

3. Images or explanatory videos of the lesson: Students could create a video or retrieve one from the web.
4. The images could be: a) Referential (representing the described object); b) Evocative (metaphors to enhance the understanding of certain concepts); c) Schematic (visual diagrams to improve comprehension) (See Figure 5).
5. A game: Created using learning apps, serving different functions: a) A game to identify prior knowledge; b) A game to assess acquired skills; c) A game to facilitate learning of educational content.
6. A voice recording of textual parts: To enhance inclusivity.

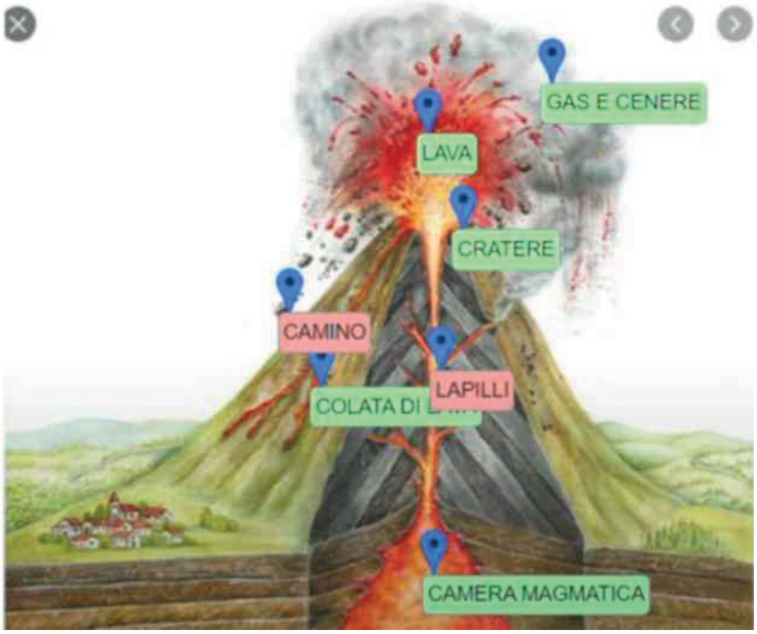

Figure 5. An example of an association game is created by learning apps.

5. Method

The analysis was conducted by applying Mayer's (2005) principles of multimedia learning using a Likert scale with values ranging from 1 to 5. The correspondence of values is shown below:

= Very low: The evaluated aspect is minimally present or almost absent.

= Low: The aspect is present but limited and underdeveloped.

=Middle: The aspect is moderately present but not fully developed or optimized.

= High: The aspect is well integrated into the product and proves effective.

=Very high: The aspect is strongly present and optimized, fully meeting the expected criteria.

A 5-point Likert scale was chosen due to its widespread use in educational research as a reliable instrument for capturing subjective judgments. It enables the identification of nuanced differences in the degree to which each of Mayer's principles is present or effectively applied. The scale offers a suitable balance between ease of use and analytical sensitivity, allowing qualitative observations to be translated into quantitative data while maintaining consistency across evaluative criteria. This approach also supports the application of descriptive and correlational statistical analyses.

Given the exploratory nature of this study, the evaluation of the projects and digital products was carried out by a single expert with extensive knowledge in media and digital communication. To ensure consistency and transparency, the assessment criteria were grounded in established frameworks and supported by current research in the field of multimedia learning.

The evaluation grid was specifically designed for this study, taking into account both Mayer's principles of multimedia learning and the affordances of emerging immersive technologies. Particular attention was devoted to ensuring a balanced integration and interaction of various multimedia modes within contemporary immersive environments, in according with Mayer (2024). This approach allows for a more accurate and relevant assessment. It is sensitive to the complexity and educational potential of advanced immersive technologies.

Table 3 provides an overview of the reference principles, their description, and a concrete example of what should be included in digital products. The Likert scale was applied to each principle.

Table 3. The table contains Mayer's principles, descriptions, indicators, and product evaluation scores.

Principles	Description	Indicators	Score
Multimedia	Use a combination of text, images, videos, and 3D models to facilitate understanding.	A lesson on the circulatory system uses an interactive 3D model of the heart, accompanied by a video or an explanatory image and short texts describing the main parts.	From 1 to 5
Coherence	Avoid unnecessary visual or auditory elements that could distract or overwhelm the student.	Avoid excessive background music or unnecessary animations in educational videos.	From 1 to 5
Segmentation	Divide content into smaller, manageable units with frequent interactions.	Break content into tasks, making use of multimedia.	From 1 to 5
Spatial Contiguity	Present related information close together, avoiding the need for students to search for it in distant areas.	For example, text labels appear directly near structures rather than in a separate window.	From 1 to 5
Modality	Use audio and images to explain complex concepts, avoiding reliance solely on written text.	An image accompanied by a narrated text, which should be concise.	From 1 to 5
Redundancy	Avoid repeating the same information unnecessarily (e.g., saying something aloud while displaying a long-written text that repeats the same content).	For example, a 3D model is accompanied by concise text points but not a long paragraph that duplicates the audio.	From 1 to 5
Personalization	Use natural and engaging language.	First-person narration or interactive questions directed at the audience to increase engagement.	From 1 to 5
Interactivity	Encourage active participation with quizzes, virtual object manipulation, and simulations.	Develop educational and playful games to encourage active participation.	From 1 to 5
Image's first	Favor images over long text explanations to enhance comprehension and reduce cognitive overload.	Instead of a long paragraph describing the water cycle, a diagram with labels and a short explanation is used.	From 1 to 5

The data obtained from the evaluations were subsequently aggregated, and various analyses were conducted, including:
- The frequency distribution of each variable.
- The average values for each variable.
- The analysis of correlations between variables.

6. Results

Starting from the frequency distribution based on the Likert scale, the table below shows relatively regular frequency percentages for all principles, with some differences for certain variables (Figure 6).

By calculating the average scores (see Figure 7), students had to pay the least attention to the following principles:

Personalization (3.26), Image's first (3.57), and Coherence, which received a score of 4.05.

The products exhibit low Redundancy (1. 55), meaning the literal transcription of text-based content into audio or video format is minimal.

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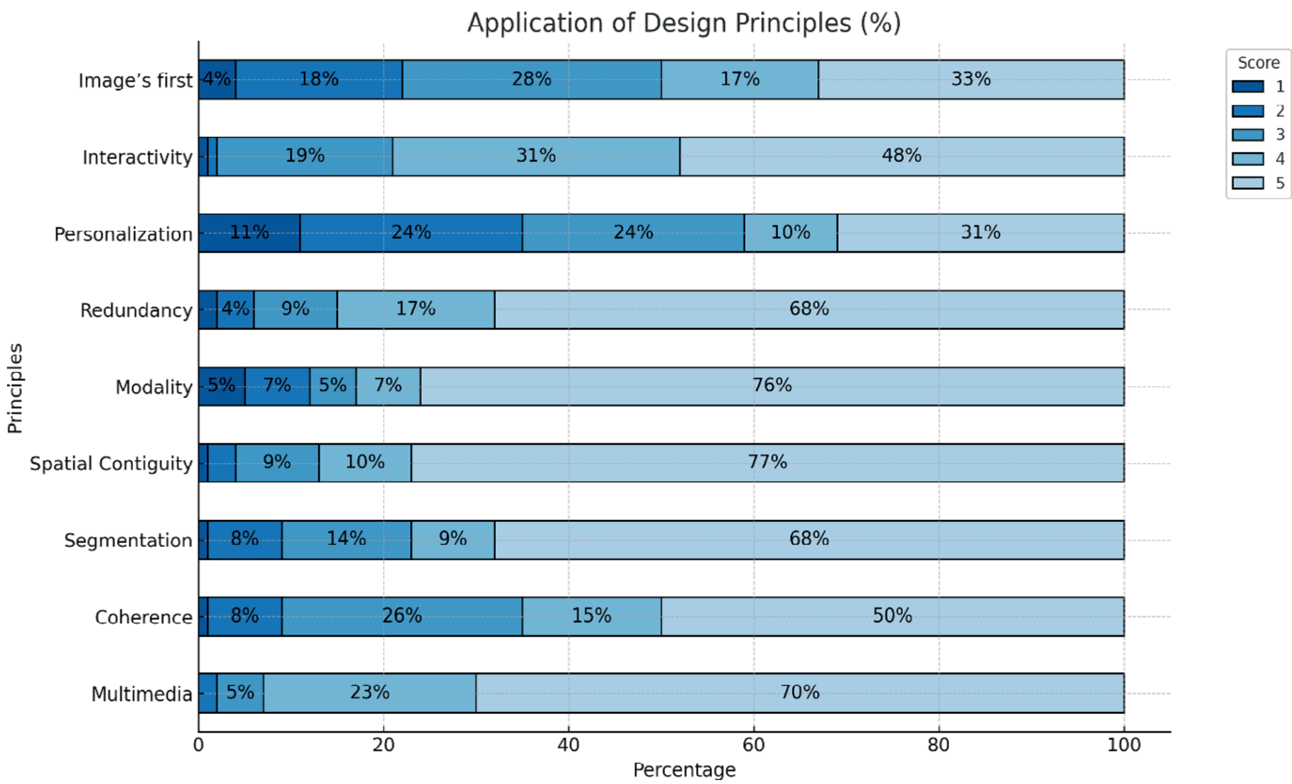

Figure 6. Frequency distribution for each principle.

Multimedia (4.61) and Spatial Contiguity (4.59) have the highest scores, suggesting that most digital products effectively integrate videos, images, and 3D models and that these elements are well-organized within the space.

Segmentation (4.35) and Interactivity (4.24) receive high scores, indicating that many digital products properly divide content into smaller modules and offer interactive activities. This confirms that segmentation is a common strategy for improving usability and engagement.

Coherence (4.05) and Modality (4.42) have slightly lower values, suggesting that some products could still improve in terms of narrative structure and Coherence between elements (text, images, audio).

Personalization (3.26) has a lower average than other indicators, highlighting that many digital products do not offer customization features to meet users' specific needs.

Redundancy (1.55) has the lowest value, indicating that most digital products avoid unnecessary repetitions of information.

The standard deviation does not indicate significant differences. Specifically, we observe that:

Lower standard deviations for multimedia (0.68), Spatial Contiguity (0.85), and Interactivity (0.86) indicate that most digital environments follow similar standards for these criteria.

Modality (1.17), Personalization (1.40), and Images first (1.23) show greater variability, suggesting that some products excel in these aspects while others lack them.

Redundancy (0.95) has a relatively high standard deviation compared to its low average, meaning that some products still include repetitive elements, although most avoid Redundancy.

In the following paragraphs, we present the results obtained for each principle.

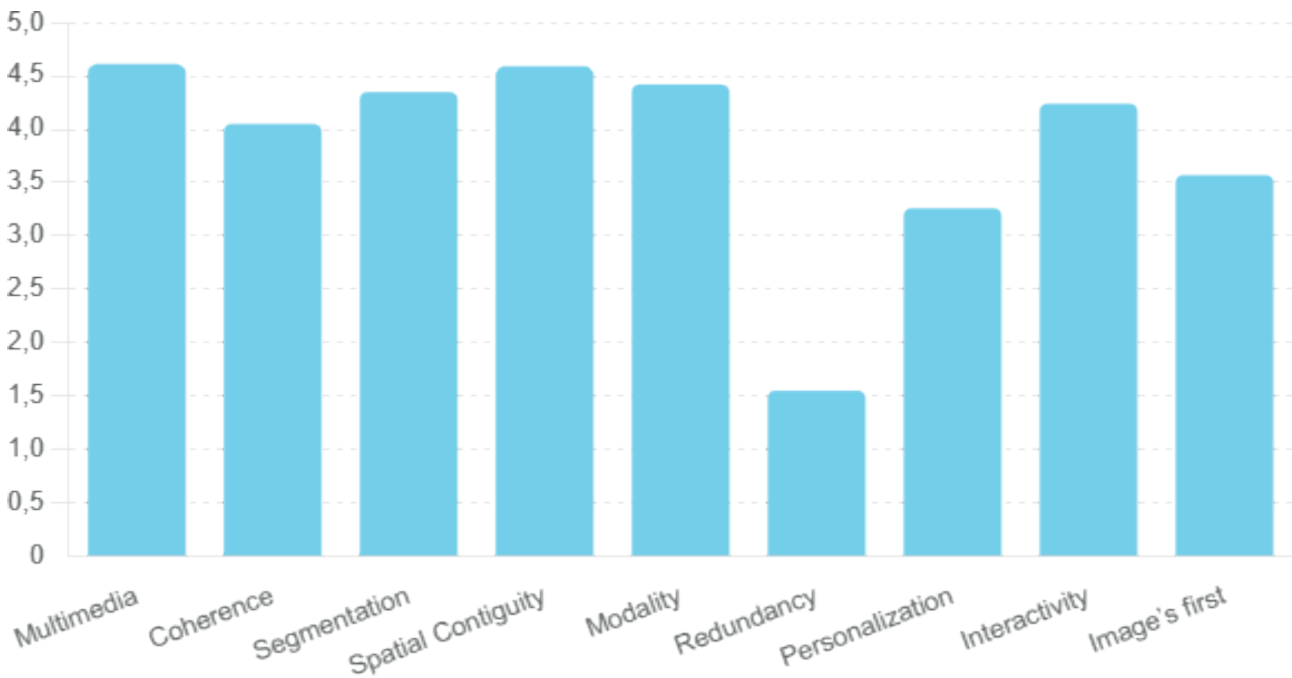

Figure 7. Average values for each variable.

6.1. Multimedia

Most of the analyzed digital products align with the guidelines regarding the multimedia principle.

Specifically, 70% of the products fully met the expected objectives, while an additional 23% showed only minor deficiencies without significantly compromising overall quality.

Conversely, the lowest percentages (5% and 2%) highlight cases where the required multimedia elements were absent, or the project objectives were misaligned with the proposed theme.

In these cases, the selection and integration of multimedia elements within the digital environment were inadequate, compromising the Coherence and overall effectiveness of the product.

6.2. Coherence

Moving on to Coherence, a significant percentage of the products (50% and 15%) adhere to this principle. However, 26% scored a three on the scale, while 8% scored a 2. Coherence was assessed based on various elements. For example, some backgrounds appeared particularly confusing and contained unnecessary elements. See the examples below.

In this Image (Fig. 8) we see numerous padlocks and many poorly connected lines, making it difficult for the user to determine where to start.

Additionally, the number of figures and objects in the background (clouds, white and grey papers, and the lighting effects near the characters in the center of the scene) tend to overlap with the interactive tags (padlocks), text, and lines inserted in the Image, obstructing a clear and linear reading of the picture. The following figure (Fig. 9) shows an image taken from an educational video featuring a distracting element. The video focuses on the anatomical structure of bee legs, associating them with the colloquial term "small tongues". However, when this term is mentioned, an image of a cat with

Figure 8. Background Thinglink example. Image created by artificial intelligence.

Figure 9. Example of a distracting image (created by Canva).

its tongue sticking out appears, accompanied by a sound effect mimicking the cat's tongue movement. This visual and auditory choice introduces a distraction, as the Image of the cat overlaps with the primary content, fragmenting attention and compromising the understanding of the scientific concept

Figure 10. Pyramid of food. Image of Ewan Sutton from Sketchfab.

being explained. Including unrelated elements in an educational video can reduce its didactic effectiveness, diverting students' focus from the main topic.

The selection of certain 3D objects can also be unclear and potentially distracting, as illustrated in the following example. The Image appears chaotic and blurry, making it difficult to distinguish between the different elements present. This lack of visual clarity can compromise content comprehension and reduce learning effectiveness (Fig. 10).

Distracting music or sounds are less frequent. In two cases, the games featured deafening music with an overly fast-paced rhythm during quiz questions. In this instance, the emphasis was placed more on the playful and educational dimensions. In one case, however, the video was sped up to the point where it prevented the reading of speech bubbles.

6.3. Segmentation

The segmentation principle highlights a relatively high percentage (68%) of selecting specific themes that support effective instructional design. Choosing well-defined topics allowed for more targeted and interactive activities, often integrated with gamification elements, to explore specific aspects of the lesson in a structured way.

However, in a smaller percentage of cases (14%), difficulties were encountered in narrowing down the topic, creating overly broad and unfocused digital products.

In these instances, materials became overloaded with information, covering an entire topic rather than focusing on specific aspects.

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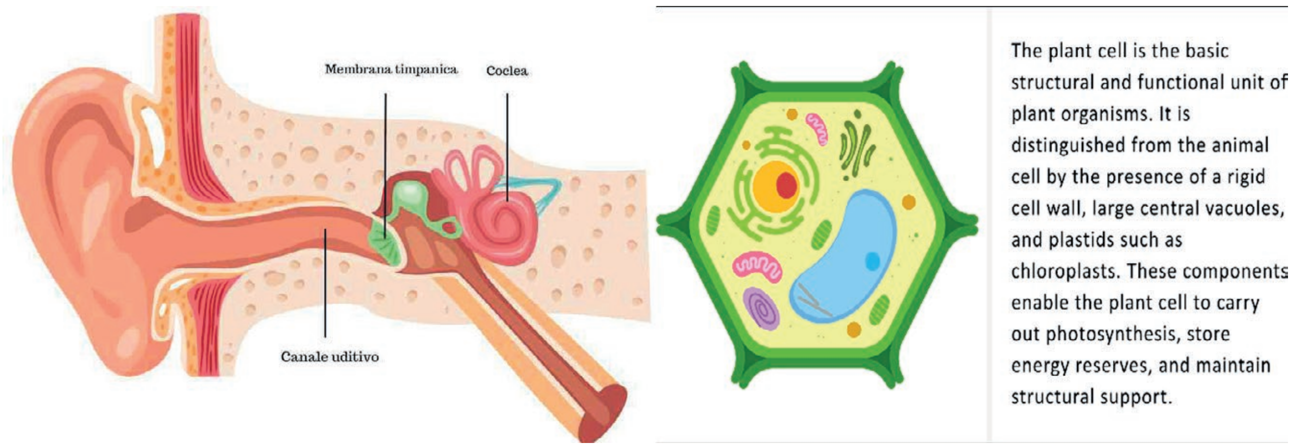

Figure 11. On the left: properly structured image. On the right is an image with adjacent text.

A notable example is slide-based videos, in which numerous aspects of a topic are presented without clear segmentation, making it more difficult for students to process the content effectively.

6.4. Spatial contiguity

Regarding spatial contiguity, most products do not present significant issues. Numerous activities include schematic illustrations annotated with labels that specify particular content, as seen in the image on the left (Fig. 11). In contrast, others present an image accompanied by a textual explanation, as shown in the image on the right in Figure 8.

6.5. Modality

Regarding Modality, the educational lessons generally featured a well-balanced presence of images and text (76%). However, in some cases, no narration accompanying the written text was present (7% scored 2; 5% scored 1). Therefore, most products use verbal and auditory channels to respect this principle.

6.6. Redundancy

Multiple communication and expression channels were often employed to explore specific concepts in greater depth. 68% of the products adhere to this criterion, while only a small percentage (between 2% and 4%) shows low compliance. Conversely, for score 3 (9%), the products contained some redundant elements but were still functional overall.

6.7. Personalization

Personalization is a particularly problematic aspect. The analysis of textual and oral communication methods reveals a heterogeneous distribution in the use of engaging and adaptive language.

31.1% of digital products use natural and engaging language. In these cases, guide characters and storytelling are widely used to support and direct the learning journey. The language is predominantly in first person, and the selected characters are consistent with the topic, fostering a more immersive and interactive experience.

24% of the products, scoring intermediate (value 3), use formal yet somewhat engaging language, especially in videos. Narrative guide characters are also present in these cases, though with less direct interaction. The language in this category oscillates between formalism and direct interaction, often characterized by explicit questions addressed to the audience, both in textual and oral forms.

35% of digital products (24% scored 2, 11% scored 1) lack communicative engagement. The formal and didactic learning environments present essential information without interactive elements. In these cases, stimulus questions are not used to engage the audience, and the language is detached, with content that may appear disjointed and static.

6.8. Interactivity

Gamification is one of the most frequently used methods to enhance Interactivity within digital environments. It is important to recall that students must include this type of activity. Therefore, an evaluation was conducted to determine whether the created games were merely digital replicas of traditional tasks (such as a classic evaluation quiz) or if they introduced innovative interactive elements.

Indeed, 48% of the games, including crosswords, horse races, name-image associations, and puzzle completions, served as problem-solving functions.

31% met the assignment requirements but mainly consisted of fact-based games, which were visually and aurally appealing but lacked deeper engagement beyond aesthetics.

3% created educational games, but these were not very playful, focusing more on text-based content.

Examples include excessively long fill-in-the-blank texts or text-based association games overloaded with visual and textual stimuli, lacking proper segmentation.

See the example below. Special attention was given to the target audience (Figure 12).

Figure 12. Image-text association game for a second-grade primary class.

6.9. Image's first

Regarding the Image's first principle, the analysis of digital products reveals a varied distribution of implementations of this criterion. A significant percentage of the products fully adhered to this principle (33% scored 5, 17% scored 4), demonstrating an effective use of images to support text and enhance content comprehension. However, a smaller proportion of products only partially integrated this aspect, where images were present but not constantly optimized regarding placement and relevance to the textual content (28% scored 3).

Finally, a minority of digital products exhibited more noticeable issues, with image placement not conducive to learning or an overreliance on text, which could compromise readability and visual impact (18% scored 2, 4% scored 1). This aspect suggests the need for greater attention to visual design to ensure an effective balance between text and images, thereby improving the user experience.

6.10. Coherence of the 3D object

Finally, the presence of a 3D object as an added value to the design was also analyzed. It was observed that the 3D object was coherent with the project and, more importantly, provided an educational benefit rather than merely being a visually appealing addition. 74% of the products exhibited these characteristics, while 26% presented some issues. One of the most common problems was choosing a topic, which inevitably influenced the selection of the 3D object.

In some cases, students selected images that did not provide clarification or additional information relevant to the topic.

In Figure 10, we present an example of the same topic addressed similarly but with two different 3D objects. Both cases explain the cycle of water. However, the first example depicts the snowflake in a recognizable and stylized form without further explanation. Moreover, the accompanying verbal and textual narrative remains at a superficial level, describing the transformation of water without providing detailed information on the differences between the molecular structure of snowflakes and that of water after the transformation. In contrast, the second figure (Fig. 13) highlights a more specific aspect: the ice molecule. Although the 3D object on the right does not convey additional information on its own, it is integrated into the chemistry-related activity, aiming to support the understanding of the chemical process underlying the transformation of water.

6.11. Results of correlation analyses

This paragraph presents the results of the correlation analysis between variables. Figure 14 displays the values obtained by calculating the Pearson correlation coefficient, which was used to identify significant associations between the examined variables. This methodology was applied to determine whether specific variables increase or decrease together. For instance, the analysis allows us to verify whether there is a relationship between content segmentation and Redundancy or whether the level of Personalization is correlated with an increase in the use of a specific presentation mode.

We observe several significant positive and negative correlations reported in Table 6, which will be discussed in the next paragraph.

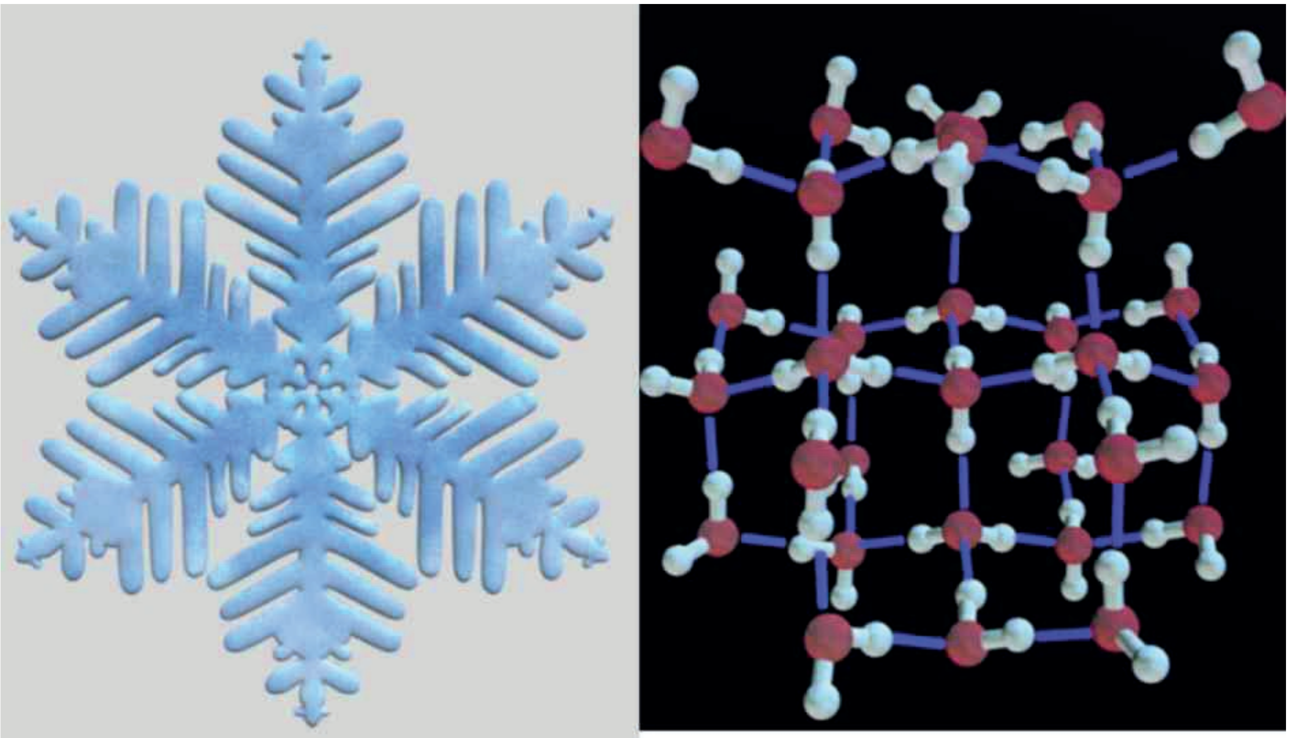

Figure 13. On the left: snowflake. On the right: ice molecule. Both pictures were taken from Sketchfab: Snowflakes (Created by Toonz Media Group); ice molecule (created by Clauter).

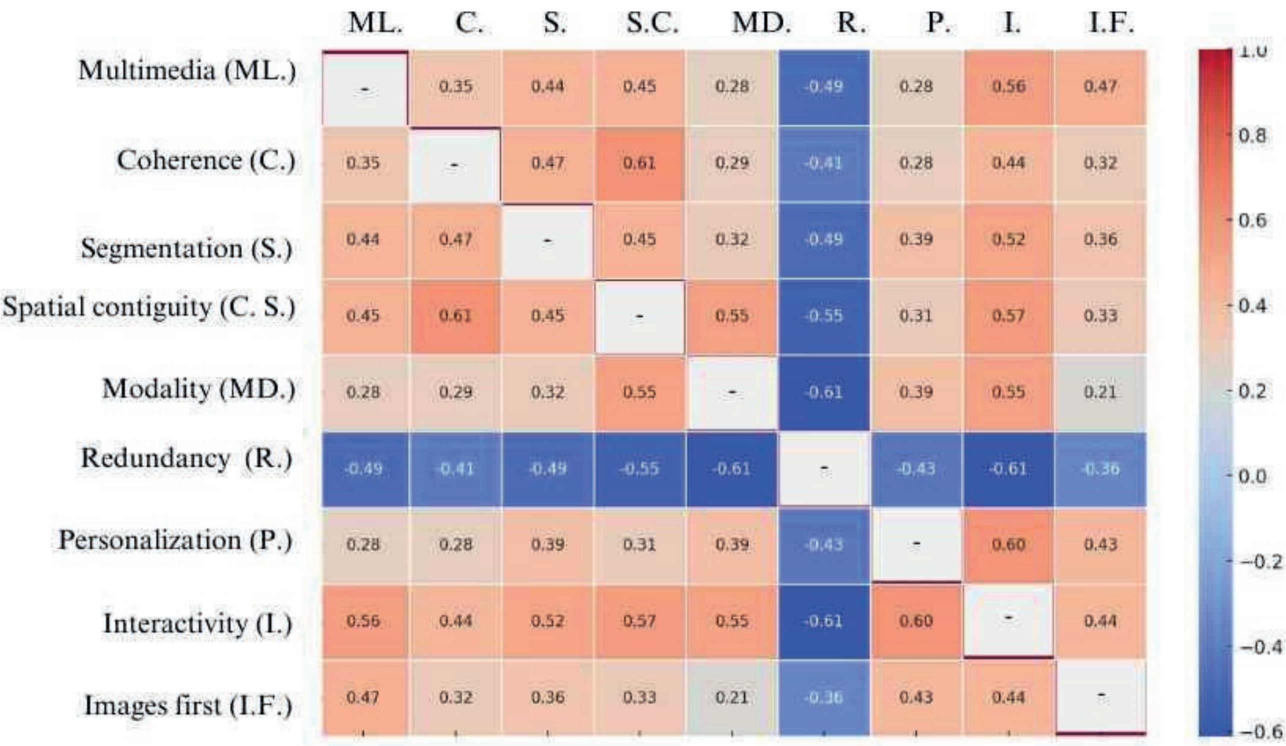

Figure 14. Analysis of correlations between variables.

Table 6. Positive, moderate, and negative correlations.

	M. & I.	I. & S.	I. & S.C.	C. & S.C.
Positive correlations	0.52	0.55	0.57	0.61
	M. & S.C.	**I.F. & M.**	**P. & I.**	
Moderate correlation	0.45	0.47	0.60	
	R. & I.	**R. & S.C.**	**R. & M. (voiceover)**	
Negative correlations	-0.61	-0.55	-0.61	

7. Discussion

The analysis of the digital products created shows that, in most cases, they adhere to multimedia principles, ensuring the effective use of multiple communication codes. However, some aspects exhibit greater variability, particularly in Coherence, Personalization, and Multimedia. One particularly interesting element is the use of first-person narration through guide characters, which has proven effective in enhancing Interactivity and facilitating a better selection of images and visual content. Additionally, integrating 3D objects within digital products has been consistent with instructional design, providing a more inclusive learning channel.

Multimedia elements have enhanced content accessibility, with only a few cases where 3D objects were out of context or educationally inadequate. The correlation analysis between design variables has revealed significant connections, suggesting important implications for designing immersive digital environments.

The strong correlation between Coherence and Spatial Contiguity (+0.61) suggests that well-structured content, free from unnecessary or distracting elements, favors an effective arrangement of text and images within digital spaces. This correlation improves overall accessibility, ensuring a clear and structured user experience.

Similarly, the positive relationship between Interactivity and Spatial Contiguity (+0.57) indicates that highly interactive learning environments featuring well-structured games tend to organize images, texts, and activities more effectively.

This aspect implies that the design of interactive experiences must consider two key aspects: a) The structure of the environment, which must include clear rules and a logical arrangement of content. b) Game design, where images, texts, and interactive dynamics must be harmonized to ensure a smooth and coherent experience.

Another significant correlation is between Interactivity and Segmentation (+0.52), indicating that dividing content into smaller modules facilitates the creation of more targeted activities, reduces cognitive overload, and improves learning experiences. Structuring educational materials into smaller units also allows for the design of more accessible games, limiting content redundancy and optimizing the informational load for students.

Not surprisingly, the positive correlation between Multimedia and Interactivity 0.55) suggests that integrating videos, images, and 3D models is key to creating more engaging interactive experiences. These findings highlight the importance of designing immersive environments with well-organized and visually aligned elements. A structured design not only facilitates Interactivity but also supports segmentation, helping to maintain high student engagement. A well-planned visual and interactive content design promotes more effective and stimulating learning.

On the other hand, negative correlations offer further insights:

The inverse relationship between Redundancy and audio Modality (-0.61) indicates that when audio narration is effective, repeating the same information across multiple formats (text, images, audio) can become redundant.

Similarly, the negative correlation between Redundancy and Spatial Contiguity (-0.55) suggests that well-organized visual content reduces excessive repetition, as clarity is ensured through the optimal arrangement of text and images.

Another interesting finding is the negative correlation between Redundancy and Interactivity (-0.61), showing that higher levels of Interactivity reduce the need for repetition. This point implies that interactive activities should be designed to promote active learning and avoid unnecessary content duplication.

Other moderate correlations suggest that:

Multimedia and Spatial Contiguity (+0.45) are closely linked: the effectiveness of multimedia elements depends on how well they are organized. Harmonizing text and images is essential for immediate and intuitive understanding.

Personalization and Interactivity (+0.60) indicate a more natural and engaging communication style enhances content and activity interactivity. The use of narrative guide characters and first-person narration allows for the creation of more personalized and structured games aligned with the narrative framework.

Images' first and Multimedia (+0.47) suggest that a preference for multimedia content correlates with using images and diagrams rather than long blocks of text. This correlation confirms the importance of visual design in optimizing learning processes.

8. Conclusions

The results of this study highlight the importance of instructional design that balances multimedia, interactivity, and content segmentation. Creating effective immersive digital environments requires a structured and coherent design that promotes clarity and navigability while avoiding information overload and excessive stimuli.

The study aimed to provide an exploratory view of the key elements to be considered in the design of augmented educational activities for future teachers, emphasizing how students tend to devote particular attention to the development of such digital artefacts.

For instance, the use of narrative and interactive tools—such as guide characters—emerged as a key factor in enhancing personalization within digital products. Similarly, content segmentation and the effective management of redundancy are fundamental strategies for reducing cognitive load and improving access to information.

Based on these findings, future research should further investigate the role of interactivity and personalization in learning processes and explore innovative strategies for more effective integration of multimedia content. Moreover, the evaluation grid and the proposed methodology may serve as an initial version of a broader assessment tool to be employed in future studies for comparing multimedia environments from different contexts, with particular attention to increasingly immersive settings.

Additionally, upcoming research could analyze how different configurations of content and interactive tools influence student engagement and performance, thereby contributing to the development of more accessible, inclusive, and effective learning environments.

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Development of an AI-based interactive tool to support radiographer training in chest x-ray analysis

Sviluppo di uno strumento interattivo basato sull'intelligenza artificiale per supportare la formazione dei tecnici di radiologia nell'analisi radiologica del torace

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ABSTRACT The increasing demand for chest X-ray examinations presents challenges in radiography education, requiring scalable and interactive learning solutions. This study presents an AI-based interactive tool designed to enhance radiographer training by providing real-time feedback, anatomical segmentation, and self-assessment features. Twenty-five third-year radiography students evaluated the tool's usability and perceived quality using a validated evaluation framework. The results indicate high learnability (3.12/4), system response time (3.54/4), and security (3.38/4) but highlight areas for improvement in stability (2.79/4) and diagnostic performance (2.79/4). The tool was generally well accepted, with moderate scores perceived benefit (3.02/4) and intention of use (2.75/4). While the AI tool shows promise in enhancing radiography education through interactive learning, further improvements in stability and user interface design are needed for broader adoption. Future studies will assess its impact on learning outcomes and clinical decision-making skills.

KEYWORDS Artificial Intelligence; Chest X-Ray; Radiography Training; Education.

SOMMARIO La crescente domanda di esami radiografici del torace pone sfide nella formazione in radiologia, che richiedono soluzioni di apprendimento scalabili e interattive. Questo studio presenta uno strumento interattivo basato sull'intelligenza artificiale, progettato per migliorare la formazione dei tecnici di radiologia fornendo feedback in tempo reale, segmentazione anatomica e funzionalità di autovalutazione. Venticinque studenti di radiologia del terzo anno hanno valutato l'usabilità e la qualità percepita dello strumento utilizzando un framework di valutazione convalidato. I risultati indicano un'elevata facilità di apprendimento (3,12/4), tempi di risposta del sistema (3,54/4) e sicurezza (3,38/4), ma evidenziano aree di miglioramento in termini di stabilità (2,79/4) e prestazioni diagnostiche (2,79/4). Lo strumento è stato generalmente ben accolto, con punteggi moderati per il beneficio percepito (3,02/4) e l'intenzione d'uso (2,75/4). Sebbene lo strumento di intelligenza artificiale si dimostri promettente nel migliorare la formazione in radiologia attraverso l'apprendimento interattivo, sono necessari ulteriori miglioramenti nella stabilità e nel design dell'interfaccia utente per una più ampia adozione. Studi futuri ne valuteranno l'impatto sui risultati di apprendimento e sulle capacità decisionali cliniche.

PAROLE CHIAVE Intelligenza Artificiale; Radiografia del Torace; Formazione in Radiografia; Educazione.

1. Introduction

A notable increase in chest X-ray examinations has been observed recently, driven mainly by the COVID-19 pandemic (Rubin et al., 2020; Smith-Bindman et al., 2019). At the same time, many radiography educators and students are still coping with the lasting effects of the pandemic on radiography education, with severe consequences in low-resource and resource-constrained settings (Tay & McNulty, 2023). These converging trends have placed significant pressure on the learning process of radiological anatomy, such as chest X-ray interpretation, which primarily relies on practical small-group teaching and tutoring sessions. Given the inherent variability of human anatomy, adequate training in this domain requires analysing a substantial number of diverse imaging cases, pointing out the need for enhanced educational resources and scalable learning methods.

Integrating artificial intelligence (AI) technologies into healthcare education presents a promising solution to chest X-ray interpretation training challenges. Specifically, the literature highlights that AI-based solutions offer multiple advantages: (i) Real-time feedback and assessment on anatomical interpretation, enabling learners to self-assess and continuously improve their skills (Chheang et al., 2024; X. Li et al., 2024) ; (ii) Personalised learning paths by adapting the educational experience based on individual performance, targeting learning on areas where students encounter difficulties (Gligorea et al., 2023; Halkiopoulos & Gkintoni, 2024); (iii) Standardised training, ensuring consistency in the delivery of educational content, reducing variability associated with instructor-dependent teaching methods (Crompton & Burke, 2023; Yu et al., 2024); (iv) Resource efficiency, since the automation of feedback and supervision reduces the need for constant instructor involvement, making training more scalable and accessible, particularly in remote or resource-limited settings (Goel, 2020); (v) and, data-driven insights by the analytics on the track learners' long-term performance, allowing educators to refine curricula and prioritise essential skills based on empirical evidence (Gligorea et al., 2023).

AI-based radiography education tools provide personalized and scalable training by acting as virtual mentors with explainable feedback with anatomic heat maps and natural language explanations, or Alteach platform that simulates patient interactions, also using natural language processing (M. D. Li & Little, 2023). Others like the Adaptive Radiology Interpretation and Education System (ARIES), allow users to compute disease probabilities from imaging features. AI can also curates comprehensive digital teaching file databases, customising case selection to align with trainees' educational needs and subspecialty interests (Duong et al., 2019; M. D. Li & Little, 2023). Beyond case-based learning, AI allows simulation environments in CT and MRI, offering preclinical training in scan planning, image acquisition, and reconstruction in radiographer education (Chaka & Hardy, 2021), and complemented with virtual reality provides physical-virtual hybrid simulations improving student engagement and learning outcomes (Acosta & López, 2024). Conversational AI, for example ChatGPT, serve as on-demand tutor for scenario creation, assessment design, and collaborative learning (Amedu & Ohene-Botwe, 2024).

Despite advances in AI-driven radiography training, existing tools typically rely on static overlays or instructor-mediated feedback, lack multi-scale anatomical segmentation, and are confine to proprietary software and case libraries. Few platforms provide real-time segmentation overlays that students can directly compare to their own annotations, nor do they allow access to heterogeneous image sources, such as open-access repositories (e.g. PadChest, CheXpert) or user-uploaded DICOMs, within a scalable, browser-based environment, Consequently, learners are unable to engage in self-paced, data-driven practice across the full spectrum of clinical variability, pointing for a critical need for an interactive, web-native platform that integrate automated segmentation, real-time feedback and unrestricted image ingestion.

This study aims to explain the conception and development of an AI platform to support chest X-ray anatomy training by providing real-time feedback, personalised learning paths, and standardised assessment methods. It also aims to assess the platform's usability and perceived quality among undergraduate medical imaging students. The article focuses on the AI tool's technical design, implementation challenges, and functional capabilities, highlighting its potential to enhance medical imaging education through automated analysis and interactive learning features.

2. Methodology

This section describes our methodology in two parts. First, it presents the design and architecture of the proposed interactive AI-based tool for radiographer training. Second, it presents the study design developed to assess the usability and perceived quality of the first version of the AI-based tool.

2.1. Design and Architecture of the AI-based tool

2.1.1. System Overview

The tool is a web-based platform designed and implemented to facilitate radiographer training in chest X-ray analysis. The platform combines modern digital technologies with AI to provide radiography students with an immersive, hands-on learning experience.

An existing library of pre-trained state-of-the-art AI algorithms is specifically leveraged to automatically obtain anatomical segmentations of chest X-rays and identify many anatomical regions, such as the lungs, heart, and spine. The platform supports iterative learning by enabling direct comparisons between user annotations and AI-generated segmentations.

2.1.2. Core Features and Use Cases

The proposed tool's key points are its ease of use, interactiveness, and personalisation, which are provided by various features and mechanisms. As illustrated in Figure 1, users can start practising analysing X-rays from the home page by interactively identifying and selecting anatomical regions. Once a specific area has been selected (see Figure 2), the selection is quantitatively evaluated based on AI-generated segmentations of the X-rays using the Dice coefficient.

This score is shown to the user, providing insights into their performance. The segmentation generated by the AI algorithm is additionally overlaid onto user selections to provide valuable feedback. AI and user selections are coloured green and red, respectively, to highlight areas of consensus and discrepancies (see Figure 3).

Moreover, practices can be carried out on X-rays provided by the tool for quick and easy set-up, or the user can upload new X-rays for personalisation. In the latter case, the ability to generalise the AI algorithm allows the provision of segmentations on unseen uploaded X-rays.

Finally, personalisation is further enriched by providing two modes: practising various anatomical regions one X-ray at a time or training to identify a specific anatomical area of their choice on several X-rays. The former allows extensive practice in identifying many areas, while the latter provides for a specific focus on a particular region.

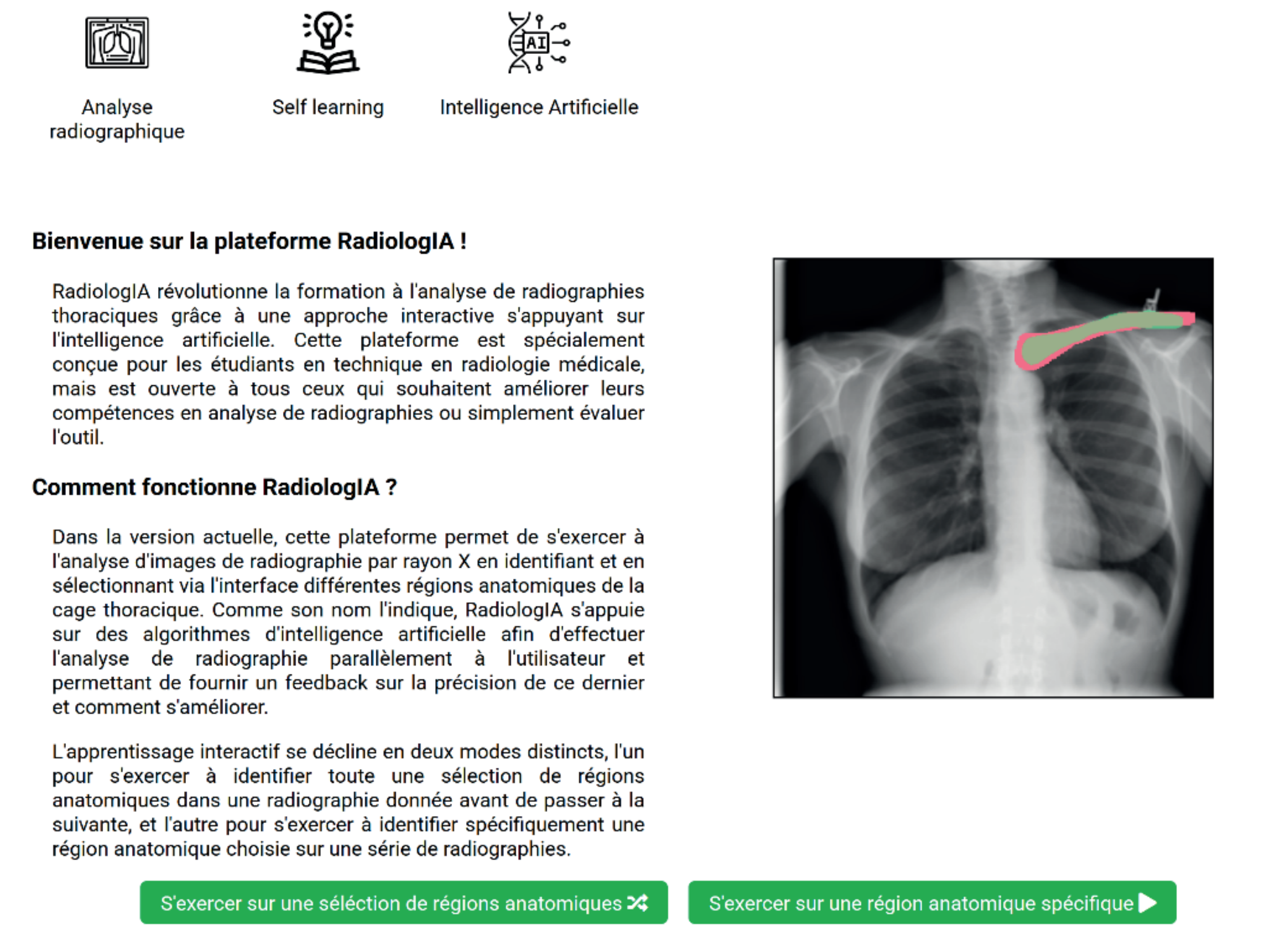


Figure 1. Home page of the platform prototype. It is composed of a short introduction and buttons to access the exercises.

2.1.3. Technical Design

The platform employs a standard three-tier architecture, dividing the system into three layers: a presentation tier (a.k.a. user interface or front-end), a logic tier (a.k.a. service or back-end), and a data tier, as shown in Figure 4.

The user interface is a web application built using Jinja2 templates. It enables the dynamic generation of web pages based on user input and back-end responses. This structure ensures a seamless user experience with responsive and interactive design elements.

The backend coordinates the overall system by serving content to the web application, receiving user inputs, running the AI algorithm as needed, and responding with the results. Moreover, it handles data management, including storing X-rays, user annotations, and feedback with the support of the data layer. Technically, the backend is implemented in Python and uses Flask, ensuring a lightweight, scalable framework for handling server-side logic. X-ray analysis relies on the TorchXRayVision library (Cohen et al., 2020, 2022). In particular, PSPNet (Lian et al., 2021) is leveraged to generate segmentations of anatomical regions from X-ray images, as detailed in Figure 5.

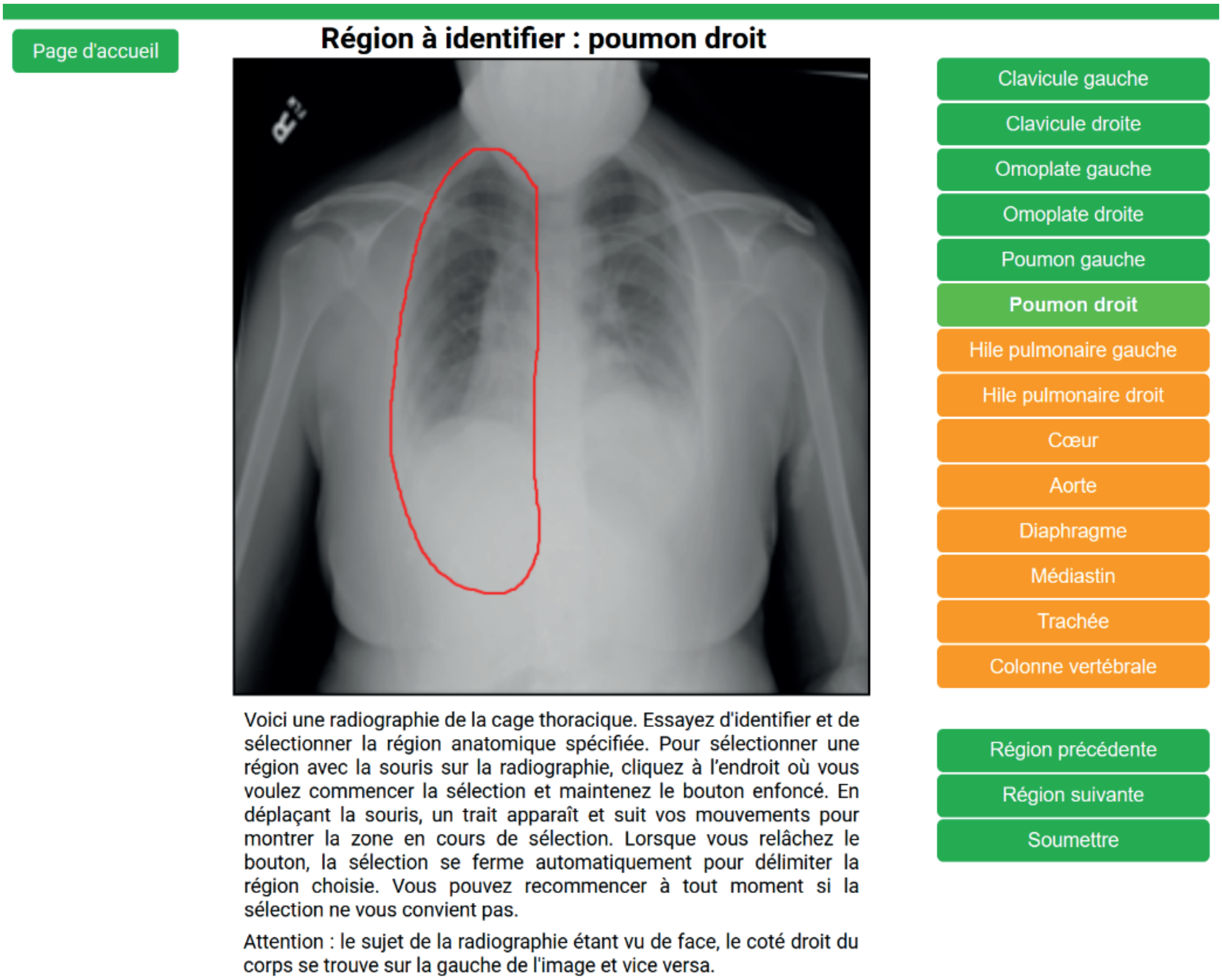


Figure 2. Exercise page: The user is asked to identify and select various anatomical areas (the right lung is supposedly chosen here).

The data layer is implemented following a hybrid approach: X-rays are stored in a file-based system for efficient retrieval and access, and segmentation masks and other metadata are stored in a relational database managed using PostgreSQL, ensuring a balance between performance and scalability. A set of predefined X-rays is made available to the user so that they can practice without having to provide them themselves. To this end, the PadChest dataset –a comprehensive open-source collection of chest X-rays with varied anatomical and pathological presentations – is the primary source of chest X-rays.

2.1.4. Data Privacy and Security

Handling medical data necessitates stringent data privacy and security measures. To this end, the current version of the proposed tool follows the principle of simplicity in cybersecurity. First, no personal data is ever asked or collected. Second, the only kind of user input is the X-rays that can be uploaded. These images stored as files are systematically renamed and solely processed by the AI algo-

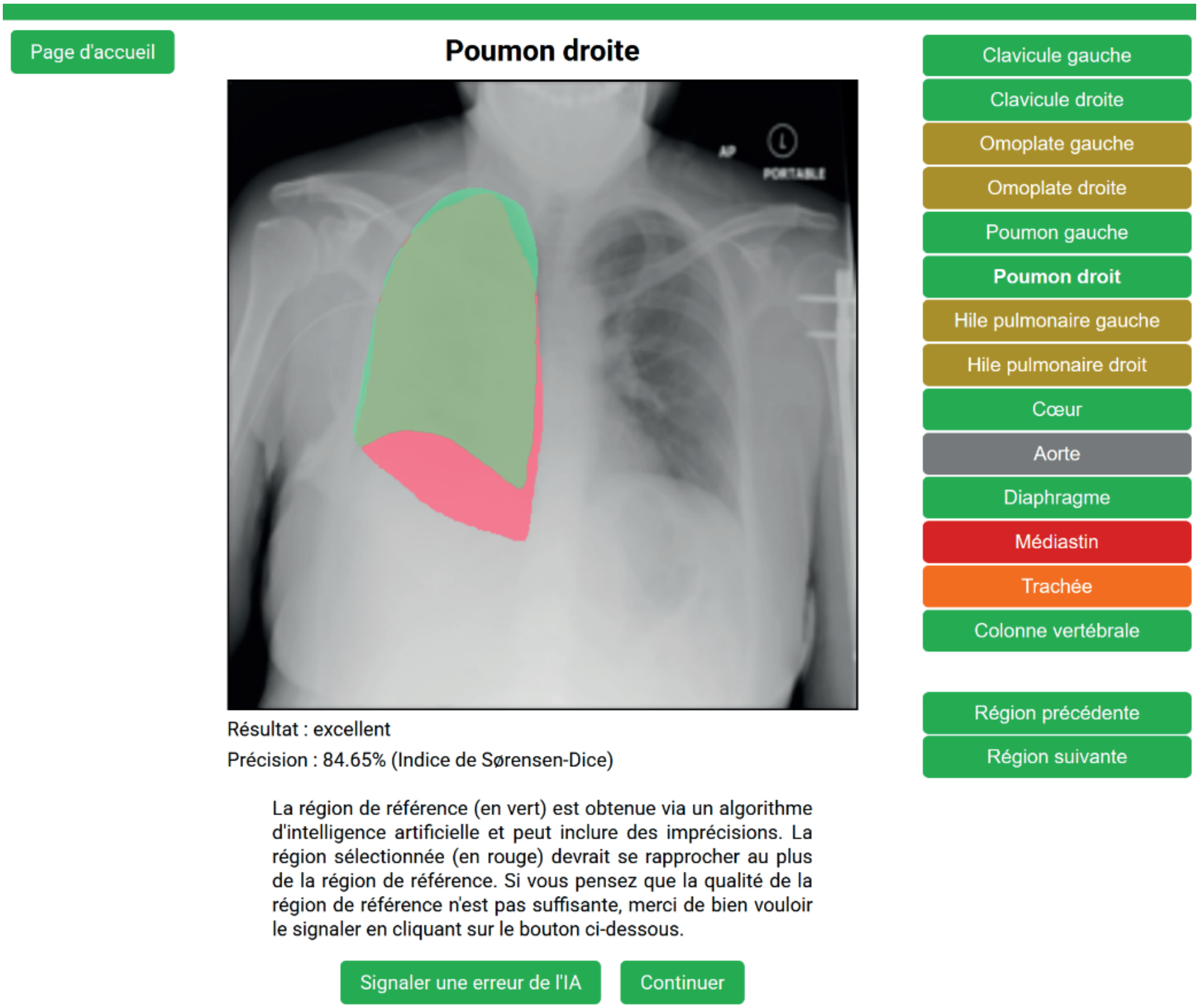


Figure 3. The results page provides insights into the student's performance. Visual feedback compares the red area (user-selected) with the green area (AI-segmented), while a performance score is based on the Dice-Sørensen coefficient.

rithm from TorchXRayVision to prevent cyberattacks or denial of service. Finally, web sessions do not contain sensitive data and are exclusively managed on the server side to avoid session hijacking.

2.2. Study design to assess the usability and perceived quality of the AI-based tool

A user evaluation study was conducted with a convenience sample (N) of 25 undergraduate students in their third year of a radiography bachelor's program to assess the usability and perceived quality of the first version of the AI-based chest X-ray training application. These participants were recruited from a university setting and voluntarily agreed to participate in the study.

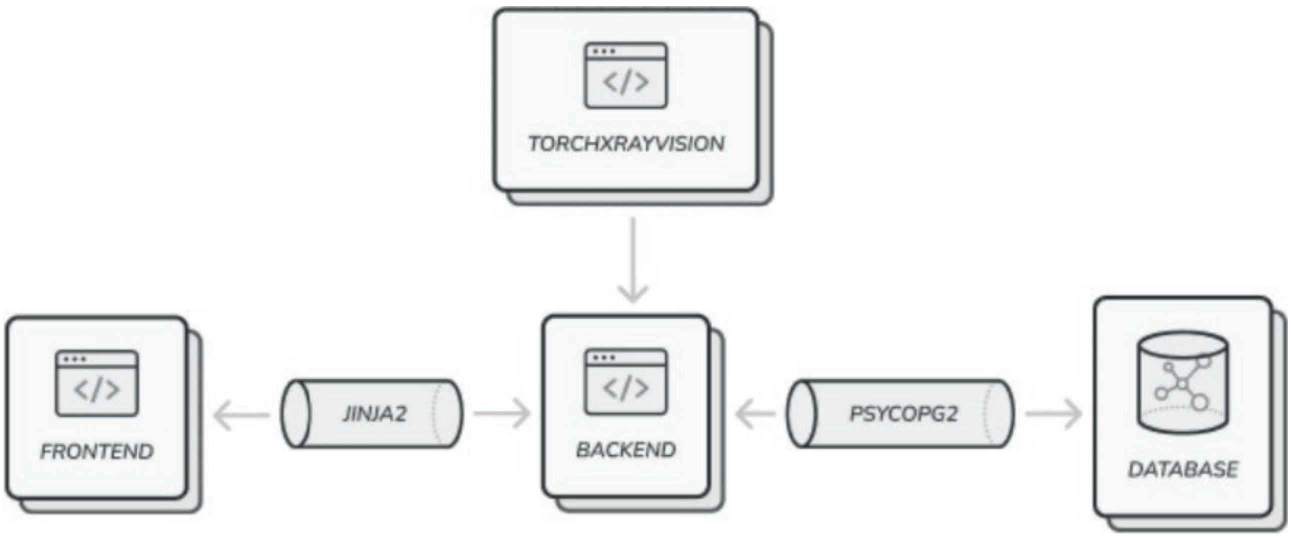


Figure 4. The application three-tier system diagram showing the UI/web front-end, the backend with the AI engine (TorchXRayVision, PSPNet), and data/storage layer (PadChest dataset, PostgreSQL).

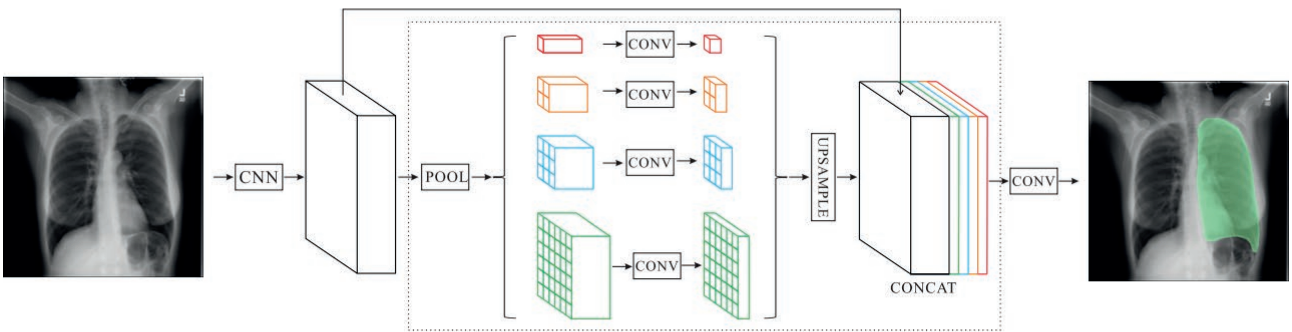


Figure 5. PSPNet segmentation pipeline: a chest X-ray is fed through a CNN backbone to produce feature maps, which undergo multi-scale pooling (1×1, 2×2, 3×3, 6×6), convolution, upsampling, and concatenation before a final convolution generates the lung segmentation mask overlaid on the original image.

2.2.1. Procedure

After briefly explaining the application, participants were given 30 minutes to explore it, utilising its functionalities across different exams and anatomical regions of the chest. After this hands-on experience, they were asked to evaluate the application using the evaluation framework for successful artificial intelligence-enabled clinical decision support systems proposed by (Ji et al., 2021). This framework includes 22 items, categorised into six key dimensions: perceived ease of use, system quality, information quality, service quality, acceptance and perceived benefit. A 4-point Likert scale was used to rate each item: 1=strongly disagree, 2=disagree, 3=agree, 4=strongly agree.

2.2.2. Ethical considerations and data analysis

This study used the principles outlined in the Declaration of Helsinki and adhered to ethical research guidelines. Participants received oral information regarding the voluntary nature of participation and provided informed consent before participating in the evaluation. To ensure data privacy, all collected responses were anonymised before analysis.

The collected data were analysed using descriptive methods, including mean, standard deviation (SD) and median for all ordinal questionnaire items and frequency distribution analysis to assess response patterns across different dimensions. All statistical analyses were conducted using Python-based libraries.

3. Results

Across all questionnaire items, median scores were uniformly 3.00 ("agree"), reflecting a general positive agreement with the application evaluated items, except for system response time in the System Quality dimension, which had a median of 4.00. Thus, mean (SD) are reported here to capture more discrete differences in user tendencies.

Within the usability and perceived ease of use dimension, the application's learnability received a mean score of 3.12 (0.77), indicating that most users found it relatively easy to learn. However, operability showed a slightly lower result of 2.84 (0.61), suggesting that its usability could be enhanced while the application is learnable. Similarly, the user interface was rated at 2.68 (0.61), reflecting the need for improvement in terms of design intuitiveness and user-friendliness. Data entry and advice display scored 3.04 (0.60) and 3.08 (0.84), respectively, showing moderate satisfaction with these functionalities. The legibility of text and information was rated at 3.24 (0.65), suggesting that the application's information presentation was clear and readable.

As shown in Table 1, the overall system quality received a mean score of 3.17 (0.77). System response time achieved the highest mean of 3.54 (0.58), mirroring its elevated median of 4.00 and indicating that users found processing and result display efficiency particularly satisfactory. Conversely, stability was among the lower-rated aspects at 2.79 (0.76), highlighting concerns about system crashes or operational inconsistencies.

Users rated information quality at 3.08 (0.64), while security, particularly critical for applications handling sensitive medical data, was given a high score of 3.38 (0.63), reflecting confidence in the system's data protection measures. However, diagnostic performance was rated at 2.79 (0.5), suggesting that users perceived limitations in the AI's accuracy and reliability in analysing chest X-ray images.

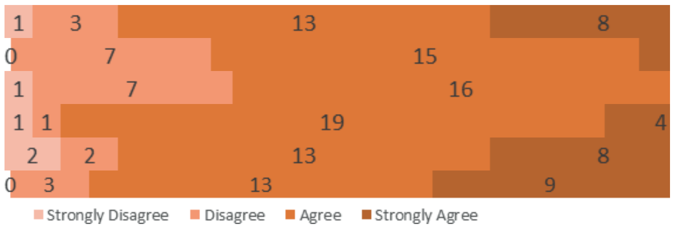
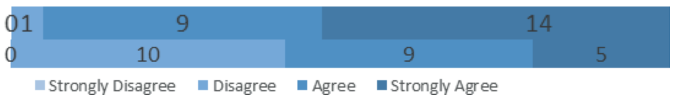
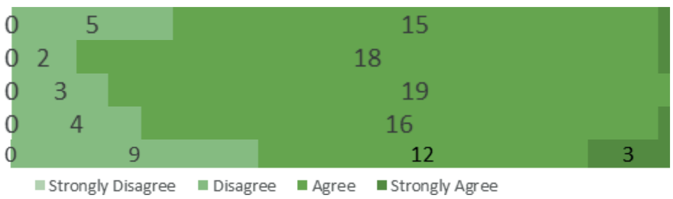
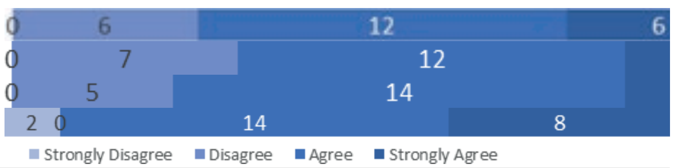
The service quality rating was 2.89 (0.73), and the operation and maintenance rating was 2.96 (0.69), indicating moderate satisfaction with system support and updates. Information updating scored 2.83 (0.76), emphasising the need for more timely updates.

User acceptance of the application was 2.96 (0.58), and expectations confirmation scored 3.00 (0.63), suggesting that while users generally found the tool acceptable, it did not exceed their expectations. Satisfaction with system, information, and service quality ranged from 2.96 to 3.08, indicating an overall neutral-to-positive perception.

The application's intention of use was rated 2.75 (0.66), indicating that while some users were inclined to continue using it, others were hesitant. Perceived benefit, a critical measure of the application's usefulness in educational settings, was scored at 3.02 (0.72). Changes in clinical decision-making behaviour (3.00, 0.71), productivity (2.92, 0.7), and adherence to standards (3.00, 0.65) suggest a moderate impact on workflow protocols. Significantly, changes in outcomes improved slightly, with a rating of 3.17 (0.8).

All described results are summarised in Table 1. to allow a systematic evaluation of the AI-based Chest X-ray training tool.

Table 1. Summary of user evaluation results for the AI-based Chest X-ray training application, presenting mean (SD) and median scores across key dimensions of usability, system quality, information and service quality, acceptance and perceived benefit.

Dimensions and items	Mean (SD); Median	Frequency distribution
Perceived ease of use	**3.00 (0.71); 3**	
Learnability	3.12 (0.77); 3	
Operability	2.84 (0.61); 3	
User interface	2.68 (0.61); 3	
Data entry	3.04 (0.60); 3	
Advice display	3.08 (0.84); 3	
Legibility	3.24 (0.65); 3	
System quality	**3.17 (0.77); 3**	
Response time[1]	3.54 (0.58); 4	
Stability[1]	2.79 (0.76); 3	
Information quality	**3.08 (0.64); 3**	
Security[1]	3.38 (0.63); 3	
Diagnostic Performance[1]	2.79 (0.50); 3	
Service Quality	**2.89 (0.73); 3**	
Operation and Maintenance[2]	2.96 (0.69); 3	
Information Updating[2]	2.83 (0.76); 3	
Acceptance	**2.96 (0.58); 3**	
Expectations confirmation	3.00 (0.63); 3	
Satisfaction of System quality[1]	3.08 (0.49); 3	
Satisfaction of information quality[1]	2.96 (0.45); 3	
Satisfaction of service quality[1]	3.00 (0.58); 3	
Intention of use[1]	2.75 (0.66); 3	
Perceived Benefit	**3.02 (0.72); 3**	
Changes in order behavior[1]	3.00 (0.71); 3	
Productivity[1]	2.92 (0.70); 3	
Adherence to standards[1]	3.00 (0.65); 3	
Changes in outcomes[1]	3.17 (0.80); 3	

[1] N = 24 due to one missing response. [2] N = 23 due to two missing responses. [a] N varies by item due to occasional missing data; all other items are based on the full sample of 25.

4. Discussion

The proposed AI-based Chest X-ray platform was successfully developed, deployed in RadiologIA and tested for its usability and perceived quality. The results indicate that the platform has demonstrated strengths in learnability, system response time, security, and areas for improvement in stability, user interface design, and performance.

The platform is innovative because it delivers real-time, interactive feedback not commonly found in traditional medical imaging training tools. The platform enhances engagement using state-of-the-art AI algorithms to generate anatomical segmentation and compare these directly with user annotations. It promotes a continuous cycle of self-assessment with real-time evaluation. This student-centric approach to the learning process is aligned with the findings of (Ji et al., 2021), where user acceptance is a central determinant of the application success, and it is influenced by perceived ease of use, system quality, information quality, service quality, and perceived benefit. In this study, perceived ease of use (learnability and operability), information quality and changes in outcome were perceived as positive, which aligns with the literature since perceived ease of use was found to be a primary predictor of learner engagement with AI tools (Müssener et al., 2020). Such positive perceptions may suggest that the potential educational impact of the tool is significant. On the one hand, standardising the training process can provide a consistent framework for learning, which can lead to improved skill acquisition among novice medical imaging students. Conversely, the interactive design may promote active learning and autonomy, allowing students to practice repeatedly in a controlled yet flexible environment.

The employed methodology ensured a structured and quantifiable evaluation of the application's usability and performance, providing key insights for future improvements and development interactions. One primary concern is the adoption by educators and students. The moderate ratings for diagnostic performance and intention of use suggest that while AI can support radiography education, users remain sceptical of its reliability in real-world educational applications. These findings resonate with previous studies on AI in medical imaging education (Crotty et al., 2024; M. D. Li & Little, 2023; Simpson & Cook, 2020), which caution against over-reliance on AI and emphasise the need for human oversight and validation, as well as the critical impact that perceived accuracy as on trainee trust and sustained use of automated analysis systems (Chen et al., 2023). Convincing stakeholders to transition to an AI-enhanced approach requires evidence of improved learning outcomes and usability. Moreover, the relatively low stability score raises concerns about system robustness, essential for the application where real-time functionality and reliability are paramount. This suggests that technical optimisations are needed to ensure the long-term sustainability of the tool and reduce errors. Ethical considerations and transparent discussions about AI's constraints will be crucial to encourage its adoption, as well as user training workshops on how to integrate AI into their learning process to mitigate scepticism.

Despite the promising results, this study reveals several limitations. First, it relied on a convenience sample of 25 third-year radiography students from a single institution, limiting generalisability. Second, the evaluation captured only immediate usability and perception metrics without assessing actual learning improvement or long-term retention. Third, the platform prototype did not undergo stress-testing under concurrent use, further system stability is needed. Finally, potential bias in the AI segmentation model was not formally assessed, stressing the need for future work on algorithmic fairness and robustness.

Under the "ChestXLAIrning" project, the next steps are to improve the technical findings report in this study, to evaluate the tool's effectiveness in enhancing learning outcomes—specifically, its impact on radiological anatomical knowledge and the interpretation of chest X-ray images—and finally, to assess the tool's acceptance, usability, and adoption among medical imaging students. The ChestX-LAIrning project aims to transform radiology education by integrating independent learning and improving clinical competencies through AI technology.

5. Conclusion

The development of our AI-based interactive tool can advance medical imaging education, offering a scalable solution that integrates real-time feedback and interactive learning into radiographer training. Through a comprehensive design process that combines modern web technologies with state-of-the-art AI algorithms, the platform provides a unique opportunity for students to engage in self-assessment and skill development with minimal instructor supervision. This innovative approach not only standardises the learning experience but also holds the promise of transforming traditional training methodologies, paving the way for more effective, data-driven, and autonomous education in the field of medical imaging.

Future studies will include improving the technical limitations illustrated in this study, evaluating the tool's long-term impact on learning outcomes and decision-making behaviour, and exploring strategies for optimising AI-human collaboration in radiography training.

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Production of a cognitive virtual reality artefact in the teaching of the History of Structural Engineering

Produzione di un artefatto cognitivo in realtà virtuale nell'insegnamento della Storia dell'Ingegneria Strutturale

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ABSTRACT The article analyses the use of virtual (VR) and augmented reality (AR) in the teaching of History of Construction at the University of Rome Tor Vergata, during the academic year (AY) 2024/25. The students designed three-dimensional experiences to explore architectural structures and understand their construction characteristics. The project integrated AR/VR as tools for constructing cognitive artefacts, evaluated in itinere. Through a case study and the analysis of a questionnaire, the links between the teaching task and the support of the learning process are explored, in particular: 1) the activation of pre-knowledge; 2) the use of metacognitive strategies, including deliberate practice and self-explanation; 3) the ability to map and verbalize learned knowledge. The results highlight the effectiveness of AR/VR in constructing epistemic representations and promoting meta-reflections in design learning processes.

KEYWORDS Virtual Reality; Augmented Reality; Architectural and Engineering Education; Metacognition; Experiential Learning.

SOMMARIO L'articolo analizza l'uso della realtà virtuale (VR) e aumentata (AR) nell'insegnamento di Costruzione dell'architettura presso l'Università degli Studi di Roma Tor Vergata, durante l'a.a. 2024/25. Gli studenti hanno progettato esperienze tridimensionali per esplorare strutture architettoniche e comprenderne le caratteristiche costruttive. Il progetto ha integrato AR/VR come strumenti per costruire artefatti cognitivi, valutati in itinere. Attraverso uno studio di caso e l'analisi di un questionario, si esplorano i nessi tra il compito didattico e il sostegno al processo di apprendimento, in particolare: 1) l'attivazione delle preconoscenze; 2) l'uso di strategie metacognitive, tra cui la pratica deliberata e l'autospiegazione; 3) la capacità di mappare e verbalizzare il sapere appreso. I risultati evidenziano l'efficacia di AR/VR nella costruzione di rappresentazioni epistemiche e nella promozione di meta-riflessioni nei processi di apprendimento progettuale.

PAROLE CHIAVE Realtà Virtuale; Realtà Aumentata; Formazione in Architettura e Ingegneria; Metacognizione; Apprendimento Esperienziale.

1. Introduction and state of the art

The use of virtual reality (VR) and augmented reality (AR) is spreading rapidly in all educational contexts, as is the research investigating its opportunities, benefits and criticalities.

A recent systematic review identifies the positive impacts of the two technologies on the work of students and lecturers with particular reference to engineering and construction studies where it is present in 27% of industrial training (Sakr, Abdullah, 2024). The specific role that virtual reality has taken on in engineering studies in recent years is evident in the possibility of experiencing and interacting with virtual environments in order to imitate real-life situations, settings, and scenarios (Zontou et al., 2024).

The main motivation for using VR and AR is the impact generated by being able to engage with simulations of reality and real environments and problems, but in safety. VR and AR provide students with an innovative teaching tool that allows them to assess the value of solutions, encouraging them to apply and acquire new knowledge and develop new skills in solving complex real-life problems (de la Torre Acha, 2024).

In the field of architecture and civil engineering, scientific studies have examined how VR and AR can be used in various ways throughout the entire life cycle of a built asset (stakeholder engagement, design support, design review, construction support, operations and maintenance support, and training), examining limitations and potential (Dávila Delgado et al., 2020).

In the field of training, a review of the literature shows how VR can offer a highly engaging and interactive medium, facilitate complex training tasks in a safe and controlled environment, enhance the learning experience by making it more vivid and memorable (Coban, et al. 2022; Kaur et al., 2022; Wu et al., 2020). Other positive effects on students' learning work concern the support of motivation, attention and active engagement; cognitive load management, concentration and memory retention resulting in increased performance and reduced errors. In addition, social functions such as collaboration and the nature of interactions also appear to be enhanced (Sakr, Abdullah, 2024).

The positive effects on the work of educators, on the other hand, relate to the increased ability to assist the learning process of students, bridging the gap between theoretical and practical concepts, and helping students to understand the task and consolidate knowledge.

Therefore, engineering teachers in higher education should consider VR and AR as complementary teaching tools compared to traditional teaching methods (Lanzo et al., 2020).

In engineering education, a review of the literature shows that VR and AR are most used in electrical/electronic/informatics and mechanical engineering courses (Zontou et al., 2004). However, cases of VR use in History of Modern Architecture courses are attested, which present some similarities with the case study presented in this article: on these occasions, advantages in the use of VR in the development of analytical and critical thinking and a high satisfaction rate were verified, with some gender-related differences (Ibrahim et al., 2021).

In contrast, limitations are identified in the high costs of start-up, maintenance, and upkeep; in the limited availability of educational software; in the burden of still very sophisticated programming; and in the possible excess of stimuli and multimedia that could burden the learning of novice students (Zontou et al., 2024). Furthermore, the lack of knowledge of technology, low usability, large time commitment for implementation and reluctance to accept a virtual substitute are pedagogical issues that need to be addressed (Yung et al., 2017). However, it needs to be emphasised that in the face of this wide use and the evidence in favour in learning contexts the didactic and methodological issues are little addressed and there is little attention to the pedagogical aspects of VR use and its impact on specific learning outcomes.

Although there is a potential coherence between technological affordances, constructivist methodologies, experiential learning and pedagogical activism-oriented techniques, these aspects emerge with less interest. In any case, when pedagogical references are present explicitly, these are attributable to active and experiential learning (59.6%), problem/project-based learning (26.9%) and collaborative learning (19.2%) (Zontou et al., 2024).

Therefore, in this framework, the analysis of the didactic factors that promote knowledge and skills through the use of VR and AR becomes important.

This paper presents the results of a research conducted with the case study methodology (Merrian, 2009) in the field of architecture and engineering education. The research was carried out with an integrated qualitative and quantitative approach through direct observation and the use of a questionnaire, and focused, in particular, on the analysis of the results with respect to the didactic task that was requested of the students, which involved the creation of an architectural environment in VR and not merely the use of a space already prepared and dedicated to a learning path.

The interest of the study, therefore, lies in the analysis of the process of creation of the VR space by the students and how this affected some variables of educational interest.

2. The case study

2.1. The Context

The study presented here concerns the activities carried out as part of the teaching of Architectural Construction at the Engineering Macro-area of the University of Rome Tor Vergata. The teaching is provided in the 5th year of the Single-Cycle Master's Degree Course in Building Engineering-Architecture and in the 1st year of the Master's Degree Course in Engineering and Building Techniques. The Italian scientific reference sector is CEAR/08 A - Architectural Engineering.

The teaching objective is to provide knowledge and skills on the History of ancient and modern construction, as well as on conservation and restoration interventions on architectural and engineering works. Consistent with the general objectives of the degree courses, students acquire in-depth knowledge of construction techniques, examined in their historical evolution and with reference to exemplary cases significant for their role in the history of art, architecture, and technology. In this way, also thanks to the development of a particular critical spirit, enriched by knowledge of the history of their disciplines, future architects and engineers acquire the ability to analyse the built heritage from different points of view and to elaborate interventions on architectural and engineering works with greater awareness.

The teaching is optional for both degree courses and is currently attended on average by approximately 10 to 15 students per year.

The teaching methods used consist of frontal lectures accompanied by practical activities and workshops, the subject of which is updated every year[1]. The frontal lectures were useful to satisfy the need to transfer some knowledge and skills in three-dimensional modelling and software application implementation in an organised way. Laboratory teaching, on the other hand, was used to carry out a practical task. In this activity:

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[1] Holder of the course is Prof. Tullia Iori, historian of construction and structural engineering. For the academic year 2024-2025, the exercises are conducted under the guidance of Prof. Gianluca Capurso and Eng. Lorenzo Grieco.

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- special emphasis was placed on the students' work together with the teacher, with the aim of fostering motivation;
- cooperative learning was used in order to create the conditions for effective collaboration and good learning, promoting interaction within groups, personal responsibility for the work and the control and revision of the work carried out;
- brainstorming was used above all in Phase 1 of the exercise, for the development of the project (see the next paragraph), during which the opportunity for students to express themselves in a completely unconstrained manner and without the risk of receiving criticism, in relation to the project idea, was valorised;
- peer tutoring relationships were fostered, as one student with more advanced skills in the realisation of the virtual reality experience and one with special knowledge in modelling provided support, explanations and feedback to their peers. The exchanges fostered collaborative learning and improved skills for all participants.

2.2. Activities carried out

For AY 2023-2024, it was decided to involve students in the direct development of an AR/VR experience related to the course topics.

The idea of carrying out this activity, in part experimental, is rooted in the evolution of the tools used for the Architectural Engineering courses at the University of Rome Tor Vergata, and in particular in those in which building history topics are dealt with: among these, the three-dimensional reconstructions of the buildings under study are particularly important.

During the frontal lectures, special axonometric cutaways are often used, elaborated by the researchers of the 'Architecture and Construction' group set up by Prof. Sergio Poretti (1944-2017) in the 1990s and then of the 'SIXXI' group on the History of Structural Engineering in Italy in the 20th century, led by Poretti himself and Iori.

The students on those courses also developed their skills by personally drawing two- and three-dimensional drawings of buildings and structures during workshop activities: graphically reconstructing the components of a construction allows students to analyse them and gain in-depth knowledge. Over the years, these three-dimensional reconstructions have been used to be visualised on paper media first, or to generate animations to be appreciated on a computer video, or to make physical models with 3D printers. The use of AR/VR technologies is, therefore, the most recent step in this transformation.

The students were then divided into four groups:

- two groups worked on experiences related to the construction of the Pantheon in Rome;
- two worked on the construction of the Palazzetto dello Sport in Rome (1956-1957), the work of Pier Luigi Nervi, the most famous Master of the Italian School of Engineering (Iori, Poretti, 2016).

The work was divided into four phases:

1) design of an AR/VR experience, which had as its object the analysis and narration of the geometric, constructive and structural characters of the assigned work;
2) two-dimensional redesign of the work under study
3) elaboration of a three-dimensional model, using up-to-date software for mesh generation, such as Sketchup, Autodesk 3ds Max and Blender;
4) realisation of the application for the use of the experience, making programming attempts.

Figure 1. Illustrations of the Pantheon experience (Group A. Bettarelli, G. Pacetti, C. Pierfranceschi).

The design phase of the experience was developed prior to the redesign and three-dimensional modelling, as the reconstruction of such complex objects must necessarily be simplified in view of the specific result to be obtained. This necessity is dictated both by consistency with the didactic objectives, which focus on the constructive and structural aspects of the works under study, and by the limited time available to the students to carry out the exercise, as well as the calculation power of the devices used.

For the Pantheon, the students therefore imagined experiences such as

– the ascertainment of the real size of the dome's coffers, imagining walking at the height of the dome's impost;
– the confrontation of the oculus with objects of surprising size;
– a play with the construction of the Pantheon involving the insertion of aggregates within a dome pattern, from the heaviest (travertine) to the lightest (pumice) passing through materials of intermediate specific weight (tuff and brick).

As far as the Palazzetto dello Sport is concerned, the students planned to allow users to enjoy an AR experience with a model similar to the "Palagioco" (Iori, 2017): it is a three-dimensional model of the Palazzetto's factory created on the occasion of the exhibition at the Museo nazionale delle arti del XXI secolo - MAXXI in Rome on Pier Luigi Nervi and held in 2010 with the consultancy of the research group SIXXI[2] of the Università di Roma Tor Vergata. In the experience, the user learns how the 60-metre-diameter dome was built, using the 'Nervi System' (Poretti, Iori 2017): an ingenious mix of a new material, ferrocement, and a new construction process, structural prefabrication.

In the two-dimensional redesign phase, the students drew up plans, elevations and sections in order to correctly model the work under study.

The three-dimensional modelling phase encountered some difficulties due to the geometric complexity of the works under study, such as: the particular geometry of the Pantheon's coffers or the double-curved surface of the rhomboid planks of the Sports Hall.

For the realisation of the experience and to compensate for the lack of some computer programming skills, the Building Blocks[3] made available by the Meta platform were used: these tools allow

[2] 20th Century Structural Engineering: The Italian Contribution (ERC Adv. Grant 2011. Tor Vergata University of Rome, PI: S. Poretti, T. Iori, www.sixxi.eu).

[3] Explore Meta Quest Features with Building Blocks (2024). https://developers.meta.com/horizon/documentation/unity/bb-overview/.

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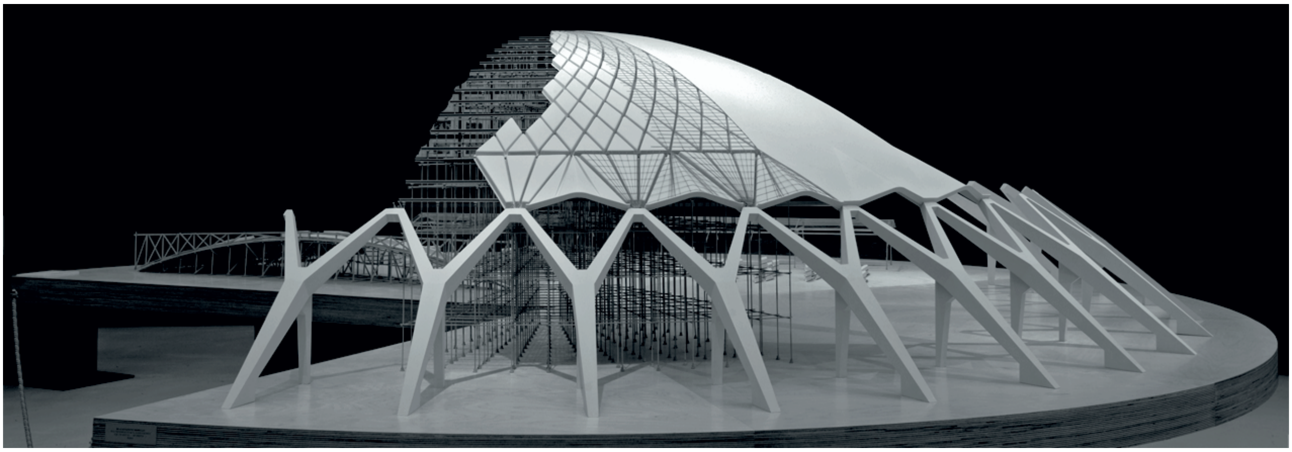

Figure 2. Overview of the completed Palagioco, MAXXI, 2010 (SIXXI Archive, Photo Sergio Poretti).

the user to set the scene and interact with certain elements of the environment, using hands or controllers.

At the end of the activity, it was possible to visualise the study objects and carry out simple interactions with the models or parts of them. It was not possible to realise all the interactions envisaged in the students' projects, as for some of them the need for specific programming skills emerged, as well as for requirements related to the development time needed.

For the next laboratory activities in the area of teaching dedicated to the sector, it is planned to realise similar experiences, particularly experimental ones in the area of engineering.

3. Research Methodology

The course presented was treated as a case study, and the teaching activities, including laboratory and in-progress evaluation, were set up to understand the type of learning experience lived by the students.

The main objective of the research was to analyse how the integration of virtual and augmented reality in construction education can influence the learning processes and the students' construction of cognitive artefacts. Specifically, the research aimed to investigate:

– the activation of pre-knowledge: assessing whether and how the presentation of anticipatory knowledge organisers (Ausubel, 1978; Preiss & Gayle, 2006) and the use of deliberate design techniques promote the recall and integration of students' prior knowledge. The aim is to understand the extent to which such knowledge is useful in tackling the task of designing and constructing digital artefacts;
– the activation of metacognitive strategies: examining the role of VR/AR in promoting conscious reflection on the objectives of the task and the strategies used to achieve them. The focus is on the effectiveness of deliberate practice, immersive experience and self-explaining (Marzano, Pickering & Pollock, 2001) in improving students' ability to plan, monitor and evaluate their own learning;
– the mapping and verbalisation of knowledge: to investigate how the design and realisation of the cognitive artefact (Wertsch, 1998; Rivoltella, 2012) can support students in organising and representing knowledge in an epistemically driven way (Nesbit & Adesope, 2006). The aim is to under-

stand whether this process contributes to the development of integrated competences, such as the ability to critically analyse and design;
- the connection between theory and practice: to explore how workshop activity allows theoretical knowledge to be translated into practical skills, improving understanding of the construction and structural characteristics of the works studied;
- the impact of collaboration and group dynamics: to verify whether cooperative learning and peer tutoring, integrated into the activities, facilitated the learning process and stimulated interaction between students, improving the final product and their reflective skills.

This research is within the framework of experiential and constructivist education, seeking to highlight not only the advantages of using VR/AR, but also the challenges associated with their use in engineering and architectural education.

The students were given a questionnaire consisting of 23 questions, 3 of which were open-ended.

The analysis of the answers to the questionnaire was conducted through an integrated qualitative and quantitative approach.

For the closed questions, a Likert scale (1 to 4) was used to collect structured data, which was subsequently analysed using descriptive statistical methods to identify trends and distributions relating to the dimensions considered: activation of pre-knowledge, metacognitive strategies and knowledge mapping.

As for the open-ended responses, a content analysis approach was adopted to identify recurring themes and qualitative patterns. In particular:
- the answers were manually coded according to predefined categories, corresponding to the theoretical learning dimensions considered, to ensure consistency with the research objectives;
- textual data were analysed to highlight how students described the use of prior knowledge, the metacognitive strategies employed during the learning experience, and their ability to organise and verbalise knowledge through task processing;
- the analysis followed an iterative process, based on the triangulation of data between the dimensions investigated, in order to ensure greater interpretative reliability.

For the closed questions, a Likert scale (1 to 4) was used to collect structured data, which was subsequently analysed using descriptive statistical methods to identify trends and distributions relating to the dimensions considered: activation of pre-knowledge, metacognitive strategies and knowledge mapping.

4. Discussion

The respondents to the questionnaire were all 10 students attending the course. Of these, 6 worked on the Pantheon and 4 on the Sports Hall. At the end of the workshop, 50% thought that the work was ready to be experienced using the visors, against the remaining 50% who stated that they did not yet have a usable product, even though the 3D experience was realised for 50% for 3 students; for more than 50% for 4 students and complete for the remaining 3.

The limited number of students involved is consistent with the logic of qualitative analysis and with the objective of generating contextualised knowledge, rather than producing generalisable statistical inferences. In this specific study, it can in fact be considered an informative sample because it corresponds to all the students who attended the course. However, the limitation is that the conclusions drawn from this study cannot be generalised without further verification, except for indications for teaching and pedagogical improvement.

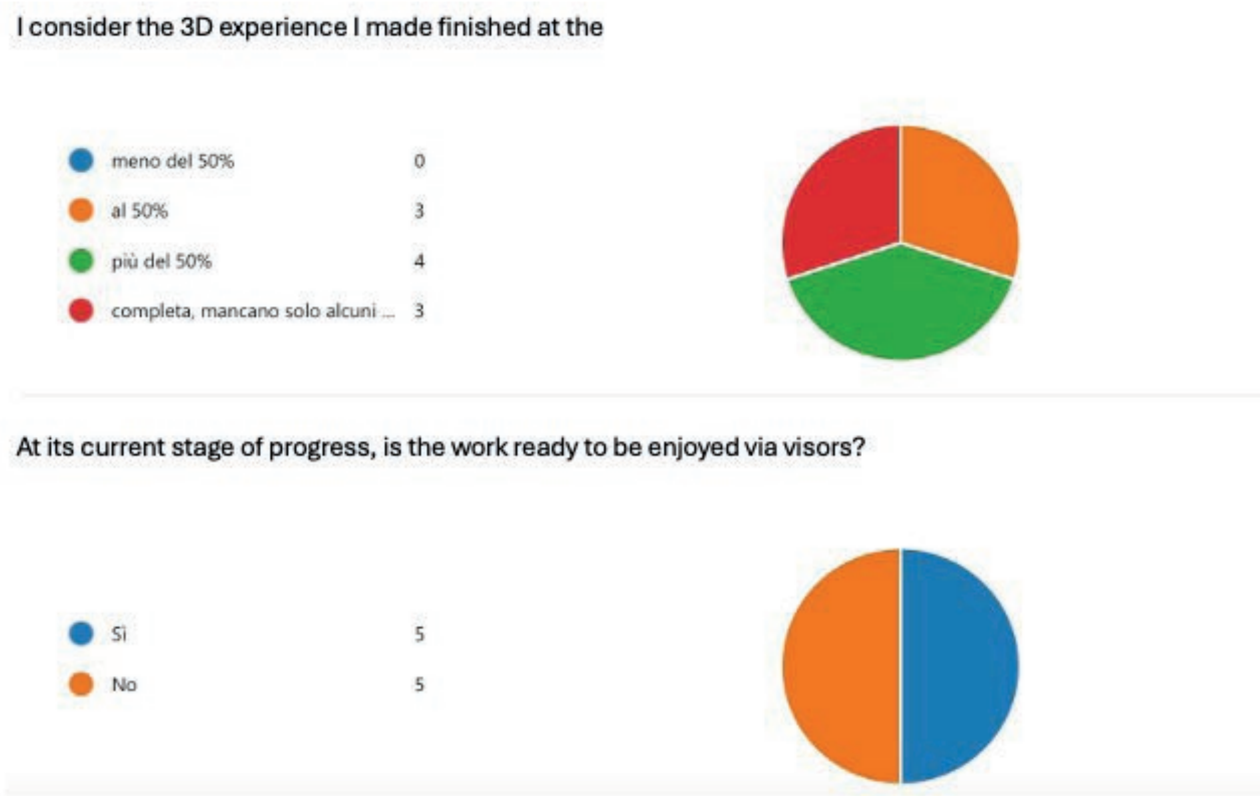

Figure 3. Completeness of the artefact developed by the students.

The answers to the closed and open questions provide a rich and articulated picture of the impact of the educational experience based on the use of virtual reality (VR) tools for the design and realisation of immersive three-dimensional artefacts.

The engagement in the elaboration of the artefact was instrumental in understanding the construction characteristics of the work they were studying for most of the students: 5 stated 'a lot', 4 'quite a lot' and only one response indicated 'not at all'. The time required to carry out the work was also assessed as quite adequate by 6 out of 10 students and in any case the commitment was quite positive for 9 students and very positive for one; also positively influencing the final examination for 50% of the respondents. However, the time factor, in spite of this generally positive assessment, was identified as one of the most critical issues of the whole experience. In fact, the relationship between time required to perform the task and perceived benefits is rather mixed: the average stands at 2.5, but the variability of responses is quite high (minimum values of 1).

The integrated analysis makes it possible to grasp both the general trends emerging from the quantitative data and the more qualitative nuances offered by the open-ended questions, and in the case of the time variable it makes it possible to identify a link with the technical difficulties encountered in producing the 3D environment. The students, in fact, highlight the need to search for information and find solutions to use 3D design software correctly and this required significant additional time, as well as the need to move independently of teachers, with only the support of the peer group.

On the other hand, the incidence of the use of VR/AR on motivation and involvement is very high: it averages between 3.4 and 3.7, with moderate variability (standard deviation of around 0.5-0.7). The

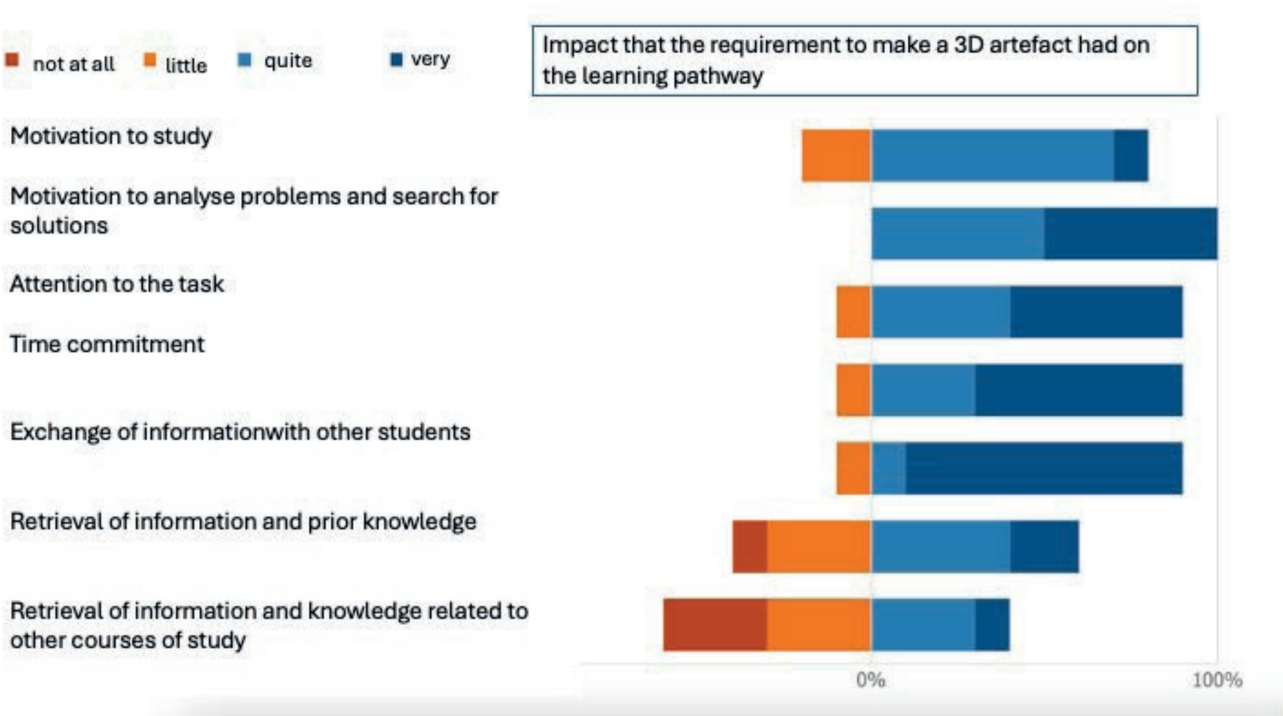

Figure 4. Perception of the impact on the learning process.

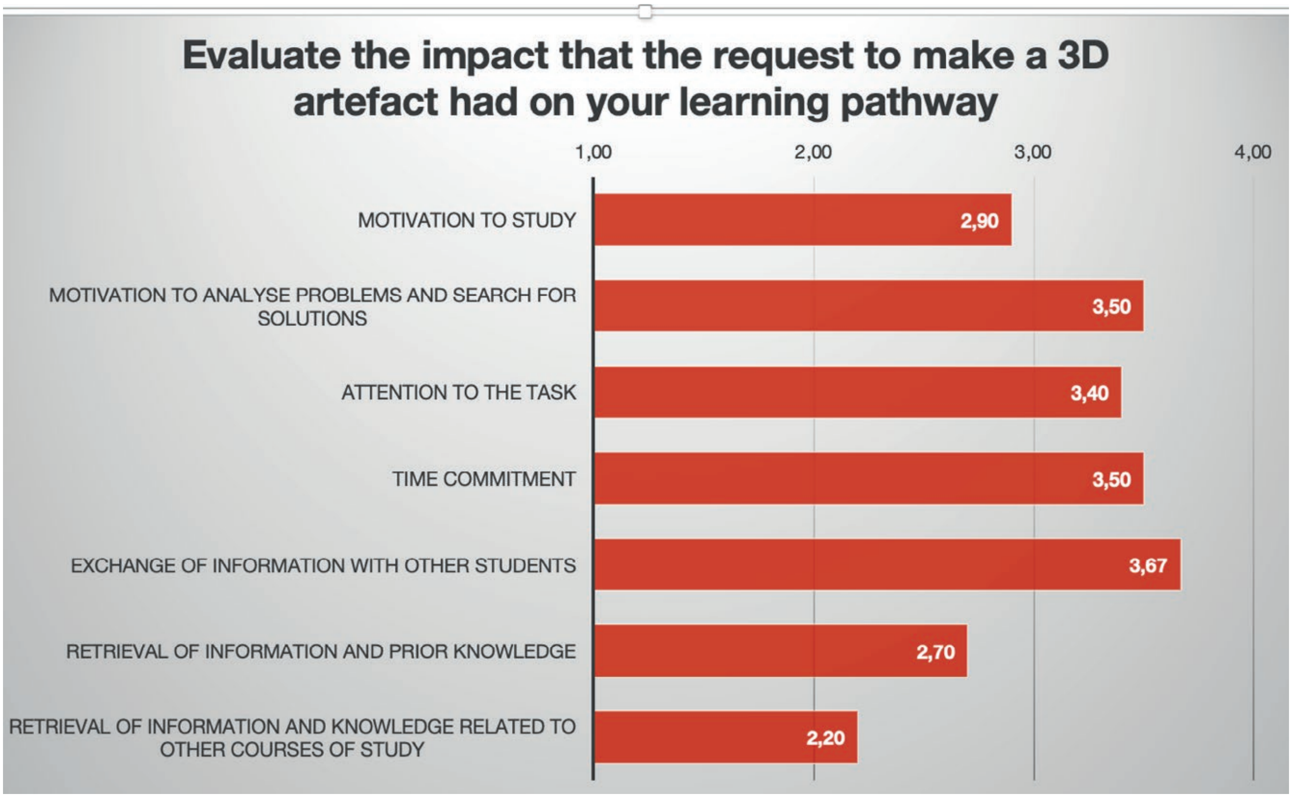

Figure 5. Average perception of impact on the learning process.

minimum score of 2 and the maximum score of 4 indicate a generally positive assessment, but with some less effective experiences.

On the other hand, the average of the answers concerning information retrieval is lower (2.2 - 2.7) and shows greater variability (standard deviation up to 0.9). This suggests difficulties in linking previous skills with the new task. It is also confirmed by the low need shown by students to find information and/or skills related to other courses (mean 1.80). This element, referring to the need to activate pre-knowledge, is certainly a point to be improved in future experiences in order to create more explicit and functional links.

On the other hand, the perception of group work is very positive: collaboration is rated positively (mean 3.4) with moderate variability (standard deviation of 0.8). Peer work and the practice of peer tutoring were helpful in achieving the objectives and enabled the students to distribute tasks, find solutions and tackle problems. Finally, the perception of the value of the skills needed to perform the task registers a mean of 3.2, confirmed by the widespread awareness of the need to possess them with a view to entering the labour market.

To explore the relationships between the construction of the cognitive artefact in VR and some key variables of the learning process (motivation, commitment, collaboration, retrieval of prior knowledge), a descriptive statistical analysis was conducted based on the responses to the closed-ended questions in the questionnaire. In particular, the data collected using the Likert scale (with values from 1 to 4) were processed by calculating Pearson correlation coefficients to identify any linear relationships between the variables.

The analysis considered the level of completion and functionality of the digital artefact (expressed through the students' self-assessment of the product's readiness) as the main independent variable and related this dimension to the degree of motivation perceived during the activity; the time and effort required; the perception of the collaborative value of group work; and the use and integration of prior knowledge.

The coefficients obtained showed moderate correlations between motivation and commitment ($r > 0.6$), as well as between collaboration and constructive understanding of the work. On the other hand, the correlation between the use of prior knowledge and the perceived quality of the artefact was weak or non-existent, suggesting a limited interconnection between prior learning and the current task. Since the number of respondents is limited ($n=10$), the results of the correlation analysis are not inferential, but offer exploratory indications useful for a more in-depth understanding of the learning dynamics activated by the virtual reality design task.

In fact, the students recognised a limited integration of skills acquired in other courses, but the experience stimulated their capacity for autonomous learning through deliberate practice, and the construction of the 3D model allowed them to concretise theoretical knowledge into digital artefacts, stimulating a deeper understanding of the constructive characteristics of the works by soliciting a clearer representation of knowledge.

Another element that emerges as significant is the year of enrolment of the students: those enrolled in the fifth year of the Single-Cycle Master's Degree Course in Building Engineering-Architecture, closer to the conclusion of their training, showed a greater ability to connect theoretical and practical knowledge, compared to first-year students of the Master's Degree Course in Engineering and Building Techniques, who show less integration of transversal skills acquired in previous courses. This evidence suggests that the year of enrolment and the degree course of origin, with the relevant skills provided, influences the effectiveness of the activity and the learning experience.

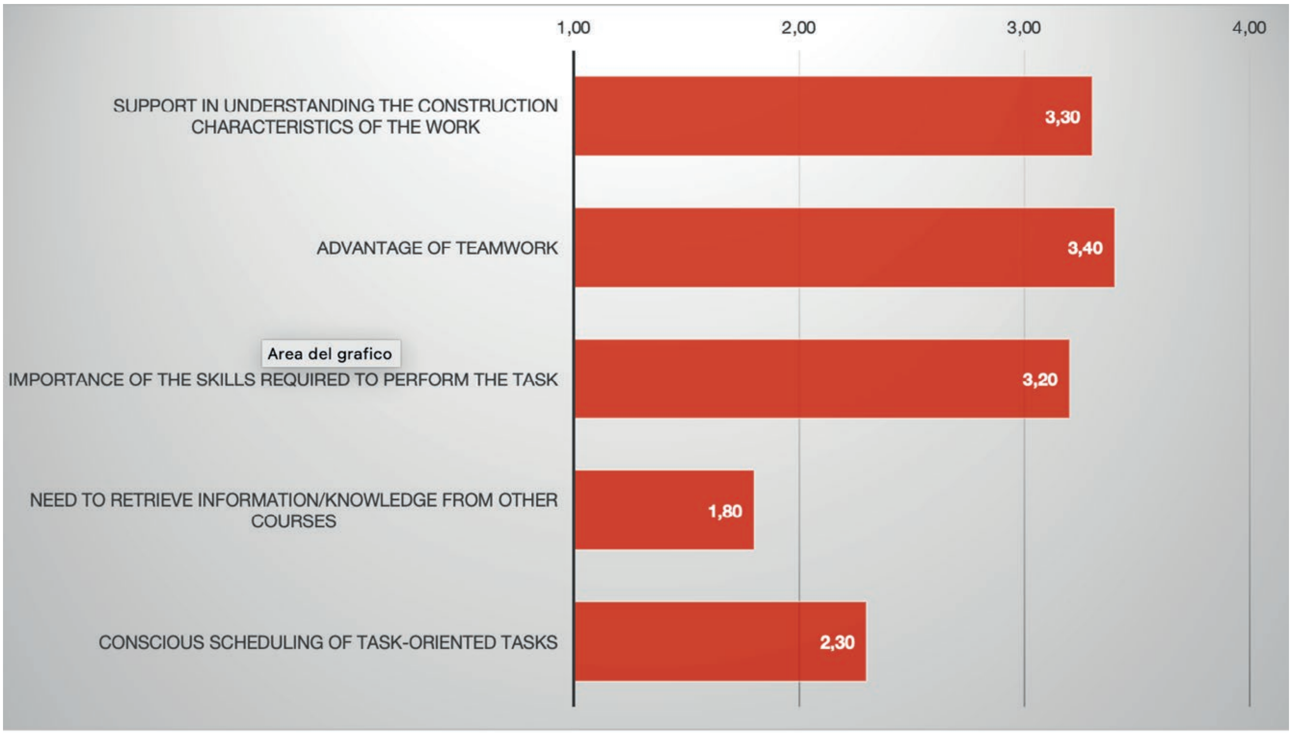

Figure 6. Influence of the task on aspects of pedagogical interest.

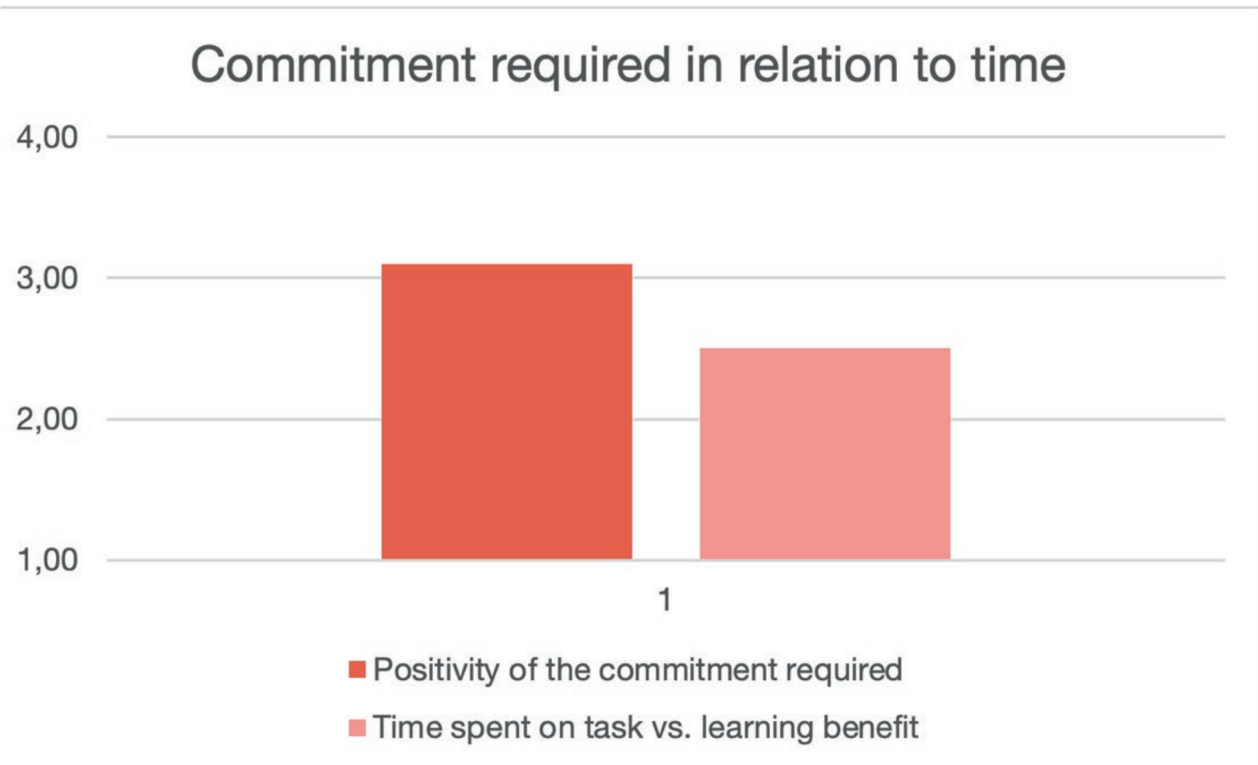

Figure 7. Commitment required and time spent.

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The answers to the open-ended questions provide a significant insight into the qualitative impact of the learning experience based on the design and realisation of three-dimensional artefacts using virtual reality (VR) tools. Some of the findings are analysed below, highlighting the main trends and linking them to the adopted analysis categories.

Most of the students stated that the experience had a positive impact, also in relation to the final exam, although with varying degrees of intensity. Some indicated that the work helped to strengthen their overall preparation and understanding of the topics covered. A significant response was: 'being the first time I used Blender, my learning was more technique-oriented, but it helped me a lot to visualise and better understand the work studied'.

The matured skills that were most frequently cited include: the acquisition of technical knowledge related to the use of 3D modelling software and a greater awareness of the integrated design dynamics between theory and practice. An example of a representative response is: 'better handling and use of 3D drawing programmes and greater ability to visualise construction details'. However, some students reported initial difficulties, often related to their limited previous experience with advanced digital tools and specific software, highlighting a gap that required additional effort to fill.

These difficulties suggest the need to introduce introductory modules or technical support at the beginning of the workshop or to include specific courses within the entire degree programme.

Among the main advantages that emerged were the in-depth exploration of complex architectural works. Regarding this aspect, one participant noted that: 'getting to know the Pantheon's structure in 360 degrees was one of the greatest advantages'; the discovery of technological potential that many students appreciated for the opportunity to familiarise themselves with software that could be useful in their future careers. In contrast, the disadvantages mentioned focus on two main aspects: the first concerns time management ('Having little time to focus on both learning the software and designing') and the second technical difficulties ('Learning independently takes longer than expected and can be frustrating').

As mentioned at the beginning, for the analysis of the experience, it was decided to use reading categories that refer to learning elements indicated positively by *evidence-based* studies (Hattie, 2013).

For the activation of metacognitive strategies, the autonomy required by the task favoured the development of actions such as conscious planning and self-explanation; this emerges in statements such as: 'to carry out the task I planned specific steps and tasks'. However, it should be noted that some students identified this element as a disorienting factor because they perceived it as unguided.

5. Conclusions and future developments

The experience proved to be a significant example of how the design of cognitive artefacts through virtual reality can promote active and integrated learning, while supporting the development of metacognitive strategies and epistemic representations. Virtual artefact design supported the development of technical and reflective skills, motivation and the integration of theory and practice. However, at present the time commitment required, linked to the need to use very technical IT and digital knowledge and skills, is still very high and represents a critical element.

A particularly relevant aspect concerns the pedagogical value of VR in enabling a deep understanding of architectural works and their construction characteristics. The possibility of 'immersing' oneself in virtual environments and interacting with the three-dimensional models allowed students to visualise the structures studied in a clearer and more detailed way, fostering not only learning, but also critical reflection on design processes. This approach proved particularly effective in creating a direct link between theoretical knowledge and practical application, strengthening students' ability to translate abstract concepts into concrete solutions.

However, the analysis highlighted the need to improve the link between prior skills acquired in other courses and the activities carried out. This aspect represents an opportunity to better integrate interdisciplinary content into the training course, promoting more coherent and transversal learning. Furthermore, the technical difficulties encountered by some students, especially those with a less advanced technical background, suggest the need to provide preparatory training courses on the use of modelling software and VR/AR tools. Such courses could include hands-on tutorials or guided learning sessions to ensure greater equity in access to the necessary technological skills.

The importance of group dynamics and collaboration emerged clearly as a crucial element for the success of the activity. Peer tutoring and cooperative learning facilitated learning, highlighting how the sharing of skills between students with different levels of preparation can represent an added value. For the future, it might be useful to further investigate the role of group dynamics, analysing whether and how they influence individual and collective performance, and assessing the effectiveness of different ways of organising collaborative work.

Another area for development concerns the possibility of using more advanced and customisable VR platforms that allow students to implement more complex interactions autonomously. The integration of such tools could be accompanied by specific training for teaching staff in order to support students more effectively throughout the whole process.

Although the experience described was developed in a specific educational context, the results obtained offer insights that can be transferred to other disciplinary and institutional contexts. In particular, the approach based on the construction of cognitive artefacts in virtual reality can be adapted to fields where spatial representation, constructive analysis or conceptual modelling play a central role, such as medicine (anatomy), environmental sciences (territorial simulations), or technical and professional training. The scalability of the approach depends on the possibility of progressively calibrating the technical complexity of the task while maintaining the educational logic that integrates active design, metacognition, and epistemic representation. The minimum replicable unit consists of an authentic guided design task, centred on a specific structure or concept, which can also be implemented in courses with larger numbers of students by dividing them into subgroups, using peer tutoring and simplifying the technical requirements. In this perspective, the proposed experience is not a closed model, but an adaptable and scalable prototype for active teaching supported by immersive technologies.

In conclusion, this experience represents a significant example of how to integrate advanced digital tools into engineering and architectural education, in the light of clear teaching guidelines. However, in order to consolidate and extend the results achieved, it will be important to address the critical issues that have emerged, planning targeted interventions to optimise working time, improve accessibility to the necessary technical skills and strengthen interdisciplinary integration. For the future, it will be useful to deepen the role of immersive technologies in promoting reflective competences, also considering the possibility of extending these practices to broader and more diverse training contexts.

A further development could be the implementation of a formative evaluation system specifically for VR experiences, capable of monitoring in itinere not only the final products, but also the students' learning process, providing continuous feedback to improve performance and promote greater metacognitive awareness.

6. Author contributions

This paper was jointly prepared by the two authors. However, the following paragraphs are identified for attribution purposes: Spinelli A. 'Research methodology', 'Discussion', 'Conclusions and future developments'. Capurso G.: 'The case study'. The paragraph 'Introduction and future developments' was written jointly.

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