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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 (Merriam, 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

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[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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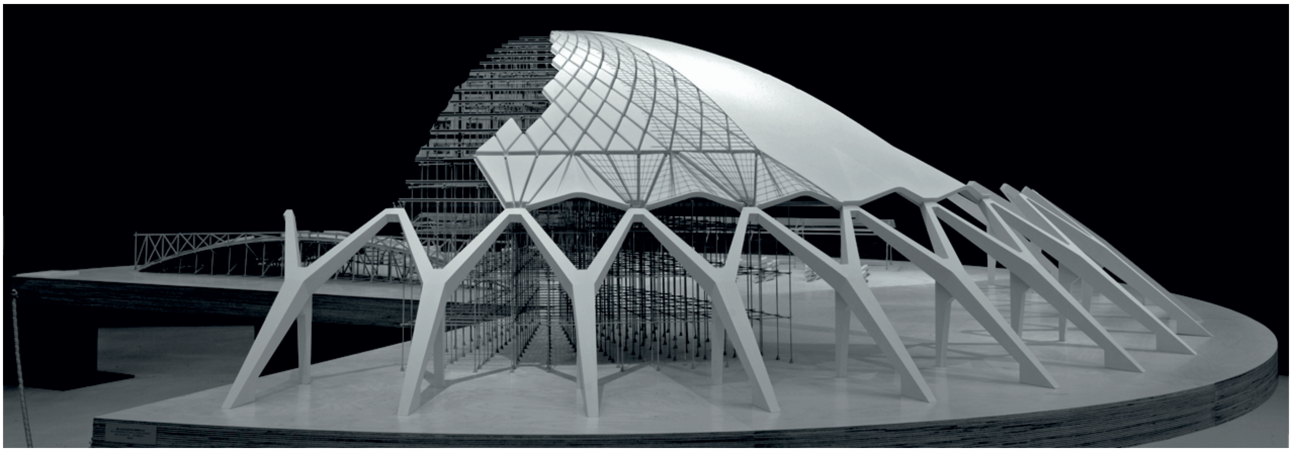

Figure 2. Overview of the completed Palagioco, MAXXI, 2010 (SIXXI Archive, Photo Sergio Poretti).

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.

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4. Results and 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.

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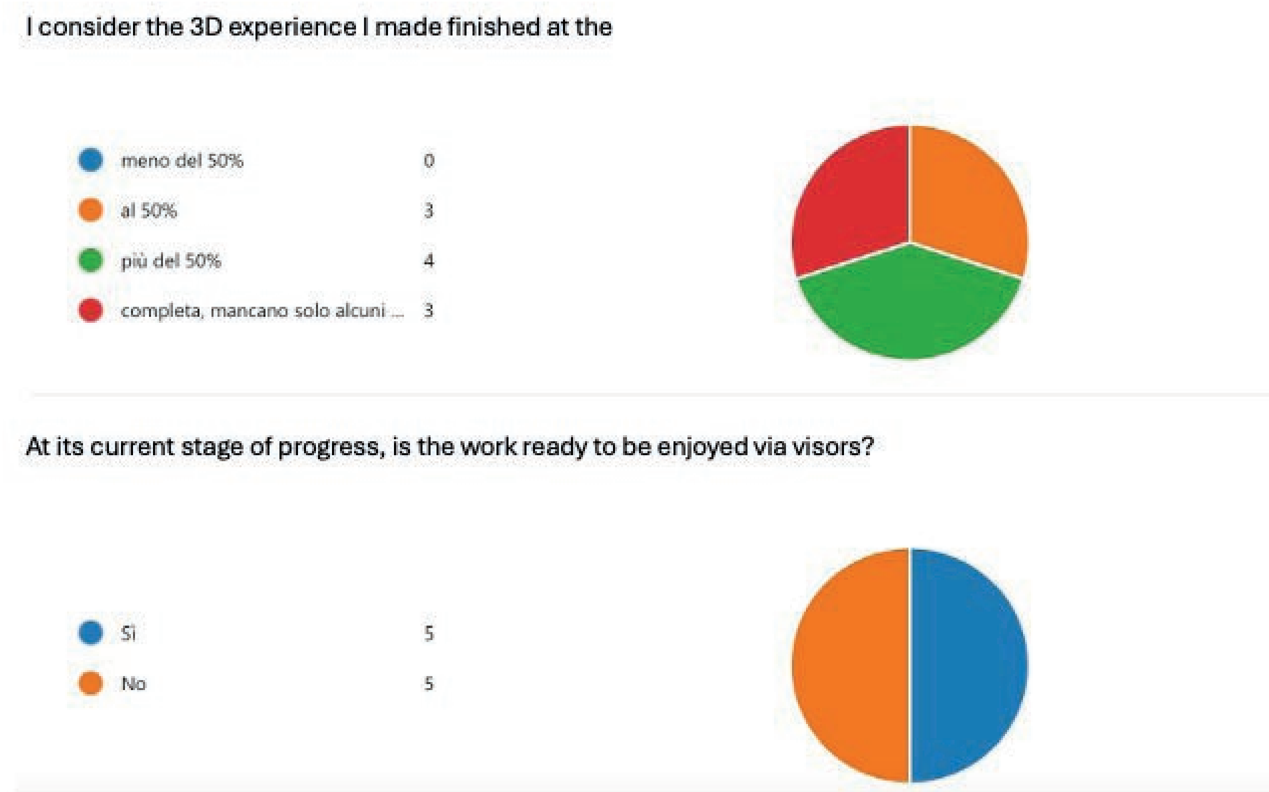

Figure 3. Completeness of the artefact developed by the students.

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

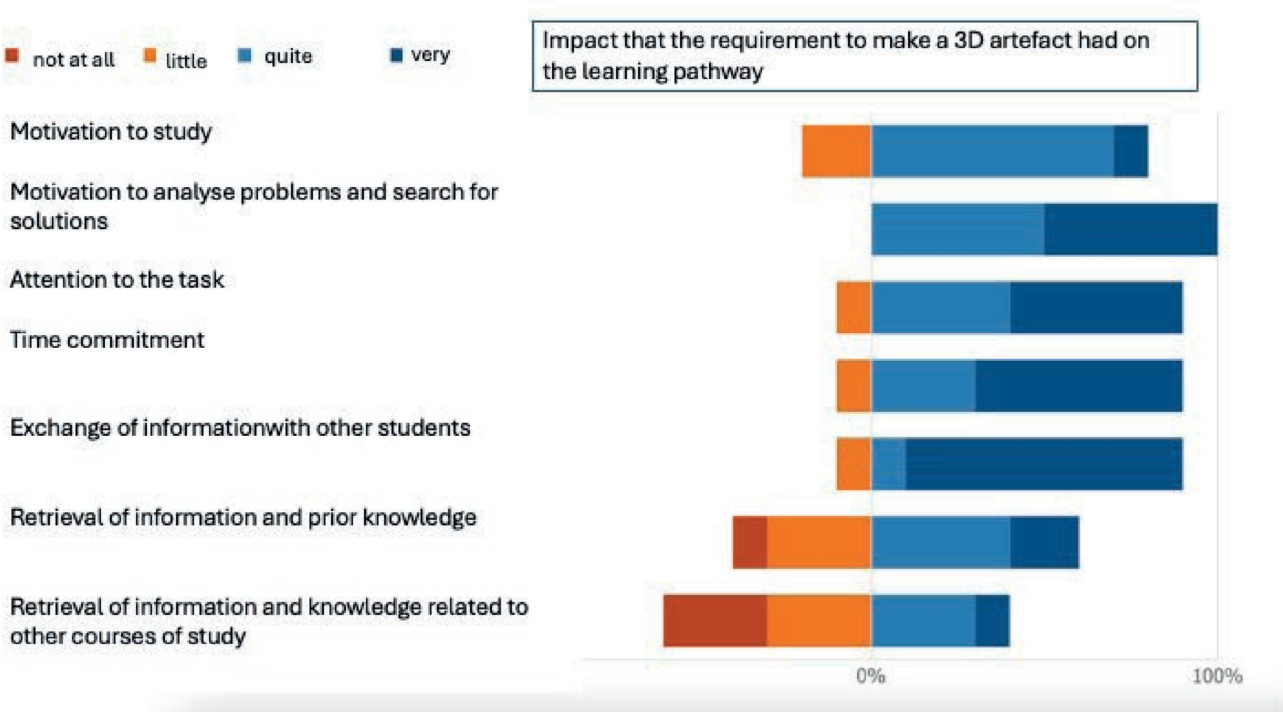

Figure 4. Perception of the impact on the learning process.

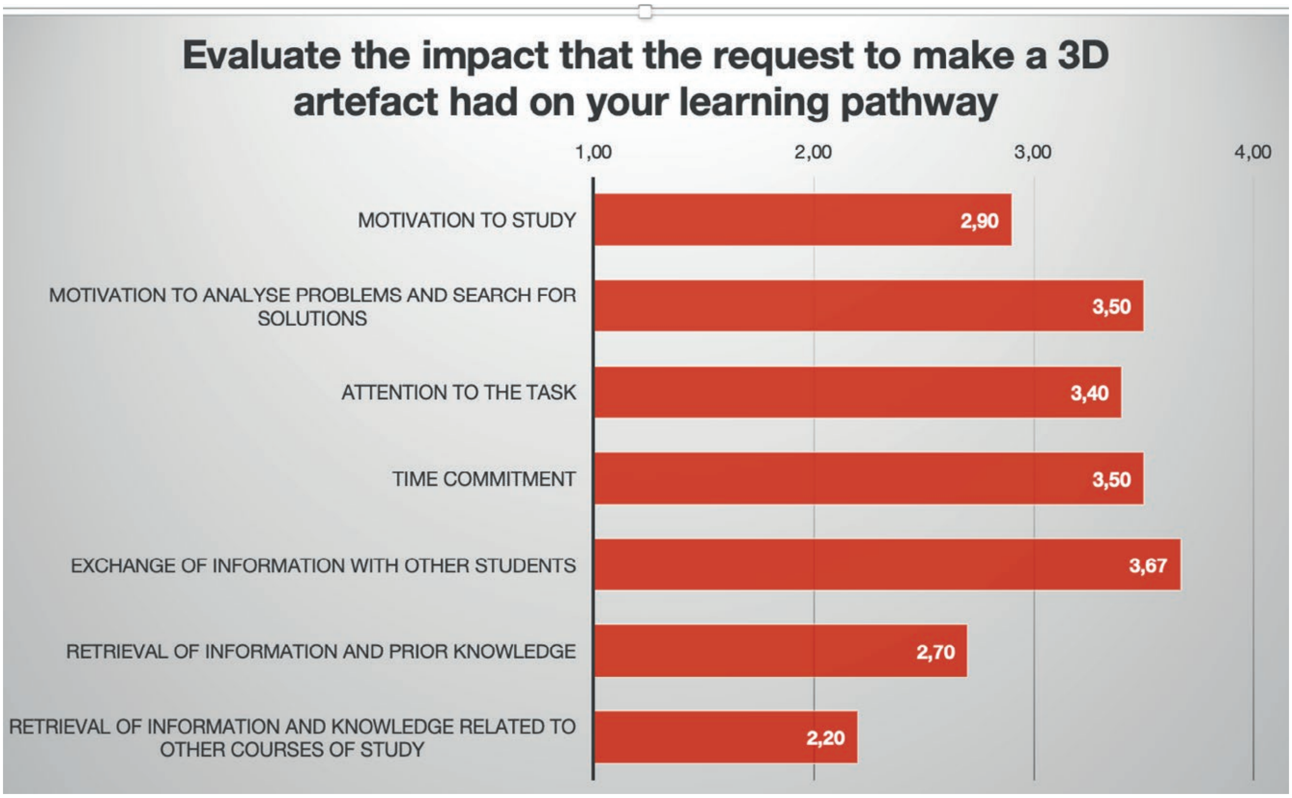

Figure 5. Average perception of impact on the learning process.

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.

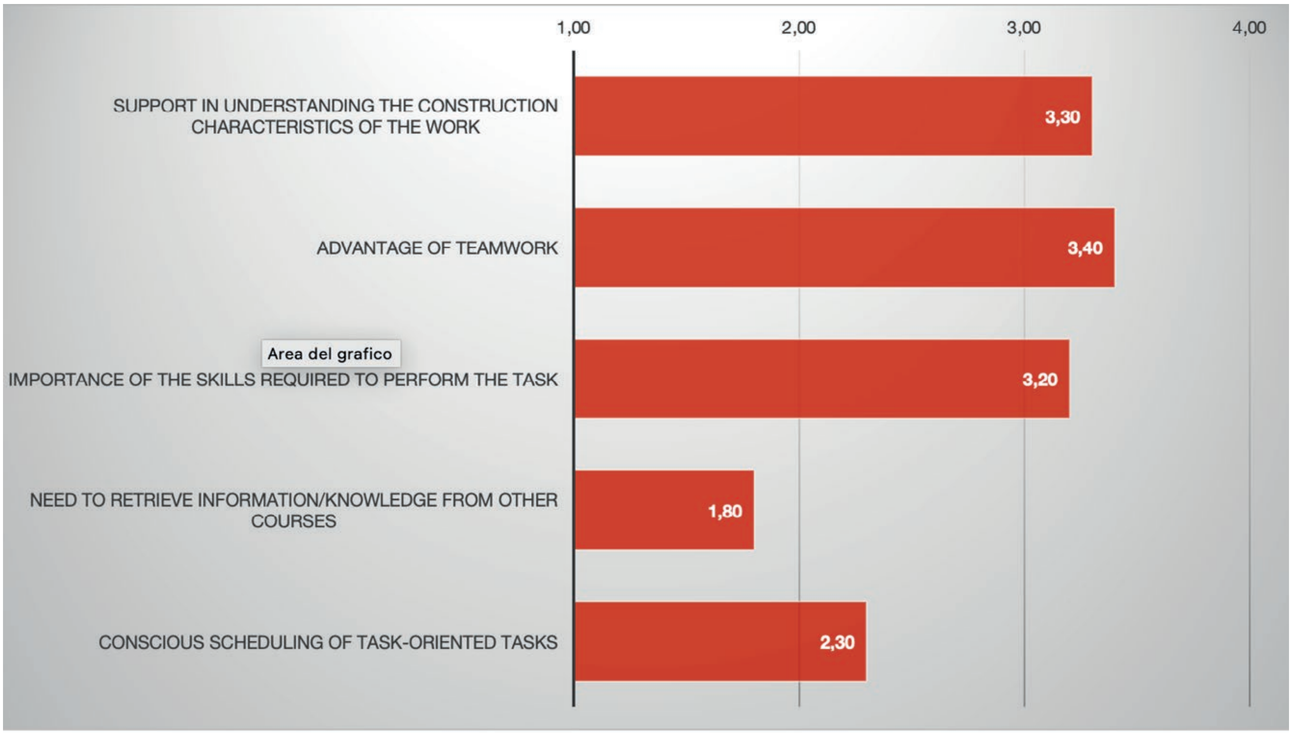

Figure 6. Influence of the task on aspects of pedagogical interest.

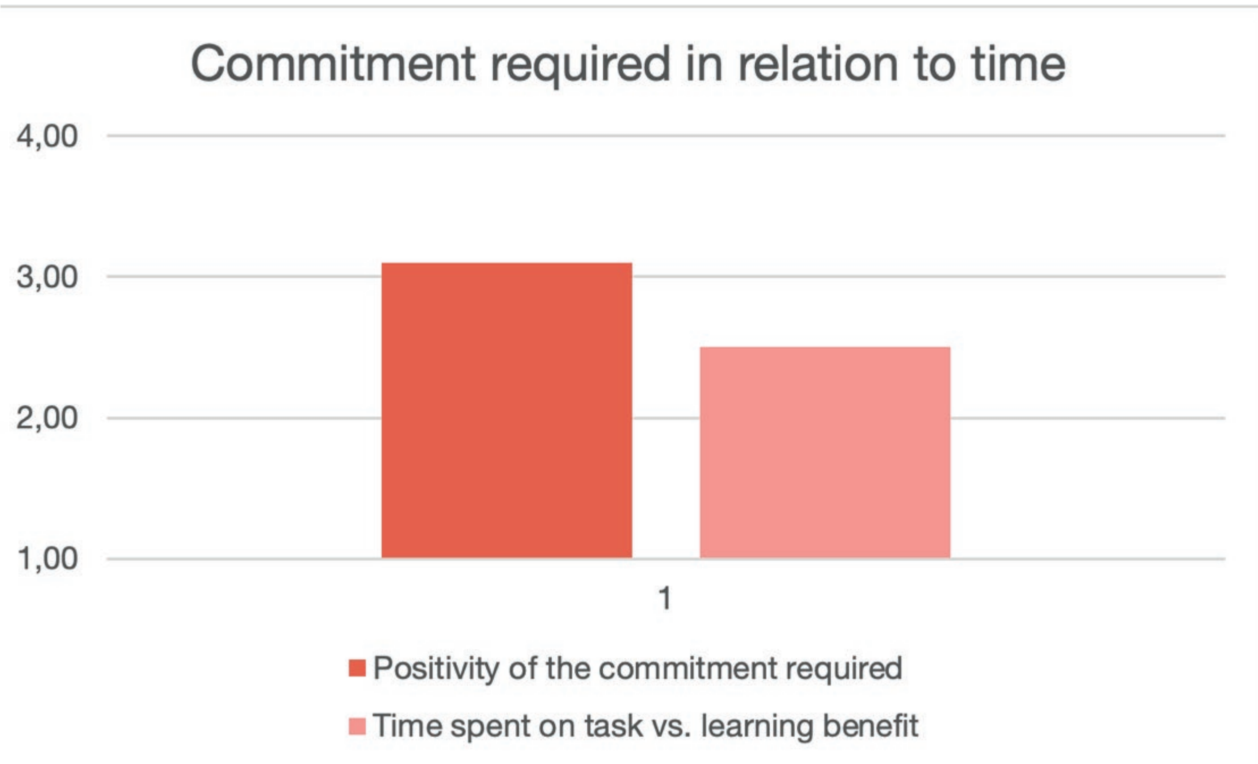

Figure 7. Commitment required and time spent.

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.

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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.

7. References

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