Immersive Virtual Environment as an Educational Resource: A Learning Tool for Data Structures and Algorithms

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Abstract. *The abstract nature of data structures and algorithms (DSA) remains a challenge in computer science education. This study introduces an educational tool using virtual reality and metaverse technologies to support DSA teaching and learning. Following a Design Science Research approach, we developed two versions: a VR environment and a metaverse platform. Forty students evaluated didactic effectiveness and usability, while eight assessed usability and immersion. Results showed significant gains in conceptual understanding ($p < 0.05$), especially for stacks and queues. Usability scores were strong (80 and 75.3), but the Igroup Presence Questionnaire score of 2.92 revealed limited immersion, potentially affecting engagement. These findings suggest the tool effectively supports conceptual learning but requires refinements in interactivity to enhance immersion and practical problem-solving. Future work will expand content coverage and address immersion gaps to consolidate its contribution to virtual learning environments.*

1. Introduction

Data Structures and Algorithms (DSA) are fundamental to computer science, underpinning fields such as software development, artificial intelligence, and embedded systems. Mastery of these concepts is crucial for designing efficient and reliable applications, as it guides decisions based on time and space complexity analysis [Riyanda et al. 2024].

Despite their importance, many students struggle with DSA due to their abstract nature, which demands advanced logical reasoning and structured problem-solving [Runceanu and Runceanu 2023]. Traditional teaching methods often provide limited contextualization and practical activities, making it difficult for learners to grasp when and how to apply algorithmic concepts [Mtaho and Mselle 2024]. These challenges frequently lead to reduced engagement, lower academic performance, and skill gaps that hinder preparedness for technical interviews and professional roles.

To overcome these barriers, recent research has explored immersive and interactive technologies as educational tools. Virtual Reality (VR) and Augmented Reality (AR) offer dynamic environments that enhance visualization, interactivity, and collaboration, fostering active learning [Li et al. 2025, Ferrari et al. 2021, Cui et al. 2023]. Examples include *OO Game VR*, which teaches object-oriented programming through immersive manipulation of virtual objects [Fernandes and Werner 2019], and AR-based tools that support the understanding of stacks, queues, and sorting algorithms through interactive visualizations [Lima et al. 2023, Ahmad et al. 2024]. While effective, many of these systems face limitations in scalability, collaboration, and long-term engagement [Fernandes et al. 2022].

Although immersive technologies have shown promise in computing education, few studies have examined their application in persistent, multiuser environments specifically designed for DSA learning.

2. Objectives

This XR prototype aims to design and implement an educational environment based on virtual reality technologies to enhance the teaching and learning of Data Structures and Algorithms. The proposed solution includes interactive virtual classrooms, algorithms' experimentation areas, and collaborative spaces for student presentations. It offers a persistent, engaging platform intended to bridge the gap between theory and practice, improve motivation, and support deeper conceptual understanding through immersive and social experiences.

3. Materials and Methods

This XR prototype follows the Design Science Research (DSR) paradigm, which integrates scientific rigor with practical applicability through six steps: (1) problem identification, (2) definition of objectives, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication.

In steps 1 and 2, the problem was defined through literature review, patent analysis, and consultations with instructors and students, highlighting persistent difficulties in learning data structures and algorithms (DSA). The goal was to design an immersive tool to enhance engagement, visualization, and intuitive learning.

Step 3 involved developing two versions of the artifact: a metaverse version (Spatial platform, web-based) and a VR version (standalone headsets), both built in Unity with C and SketchUp. The virtual island comprised an auditorium, gallery, and domes dedicated to interactive DSA learning.

Step 4 focused on demonstration. The metaverse version was tested with 40 computer engineering students in a DSA course, using pre- and post-tests to measure learning gains. The VR version was tested with 8 engineering students enrolled in a virtual reality course, selected for their ability to provide feedback on immersion and visual fidelity. Sessions lasted two 90-minute blocks. (Figure 1) Illustrates a student interacting with the prototype environment during these tests

Step 5 evaluated effectiveness and usability using a mixed methods approach. Learning outcomes were measured with pre/post-test comparisons (paired sample t-test), while usability was assessed with the System Usability Scale (SUS) [Brooke 1996]. For VR, the Igroup Presence Questionnaire (IPQ) [Schrepp et al. 2017] was also applied to evaluate immersion.

Finally, step 6 consists of communicating the results in this article. The study was approved by the SENAI CIMATEC Ethics Committee (7.012.542), with all participants providing informed consent. Experiments were conducted in March–April 2025.

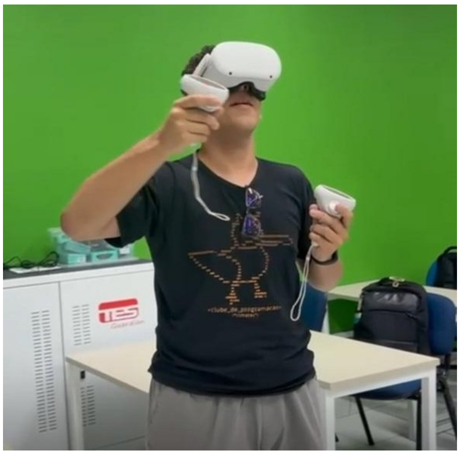


Figure 1. Student Experiencing the Environment

3.1. Immersive Environment Design

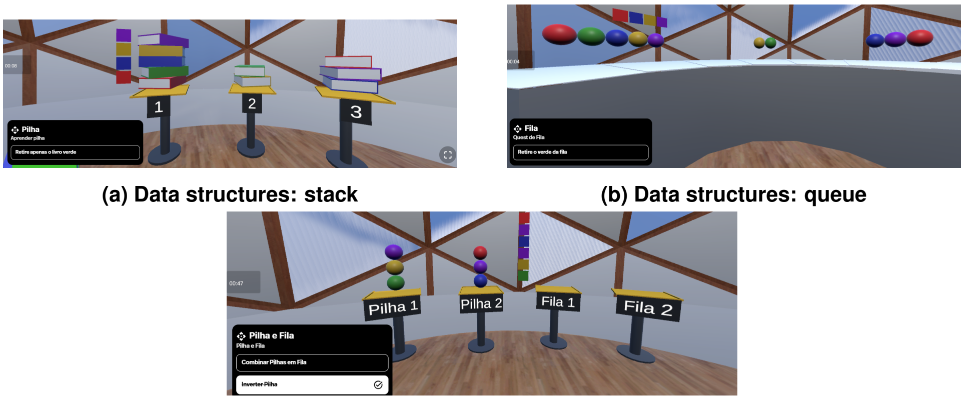
An immersive virtual environment with island-inspired visuals was created designed to foster a calm and engaging learning experience. The choice of natural and serene imagery was intended to reduce the cognitive pressure commonly associated with technical subjects, promoting a more relaxed learning environment.

At the core is the dome area, designed for interactive, gamified learning. It includes three domes focused on key data structures: stack , queue, and a hybrid dome combining both (Figure 2). Each dome introduces concepts through signs and guides users through progressively difficult quests that build understanding. A timer and progress tracker encourage replayability and reflection. The final dome integrates both structures, allowing students to apply what they've learned in more complex scenarios, reinforcing mastery through active engagement.

3.2. Assessing educational impact

To evaluate the impact of the immersive environment on the understanding of data structures and algorithms (DSA), a five-question test was applied before and after interaction with the metaverse version of the tool. Forty undergraduate students enrolled in a DSA course participated using desktops or laptops. The questionnaire covered both theoretical and practical aspects of stacks and queues. The results showed clear improvements in theoretical knowledge, particularly in general DSA concepts and understanding of stacks and queues, while the performance on practical application questions remained unchanged.

A paired sample t-test confirmed these results, showing an increase in average score from 3.05 to 3.9 with reduced variance. The test yielded a highly significant result



(a) Data structures: stack

(b) Data structures: queue

(c) Data structures: stack and queue

Figure 2. Overview of the Environment the prototype XR

($p < 0.0001$), indicating that learning gains were directly associated with the immersive experience.

Usability was also evaluated using the System Usability Scale (SUS), which achieved a strong score of 80. This suggests that the environment was intuitive and easy to use, allowing students to focus on learning. Overall, the tool proved effective in reinforcing conceptual understanding of DSA, though further refinements are needed to better support the transfer of knowledge to practical problem-solving.

3.3. Assessing immersion and visual fidelity

To assess visual fidelity and immersion, eight students enrolled in a virtual reality course tested the prototype learning environment using headsets. Although most had little prior knowledge of DSA, their familiarity with immersive technologies allowed them to provide informed feedback on usability and presence.

A 24-item questionnaire was applied, combining the System Usability Scale (SUS) and the Igroup Presence Questionnaire (IPQ). The SUS score of 75.3 indicated good usability, although participants reported difficulties in interacting with small or widely spaced buttons, which increased frustration and cognitive load. The IPQ score of 2.92, below the baseline of 3.38, revealed a limited sense of immersion. Students noted reduced engagement, attributing it to the lack of visual richness and interactive features.

Overall, the tool was considered usable and educationally valuable, but improvements in interaction design and immersive elements are necessary to strengthen engagement and presence.

4. Conclusions

The XR prototype demonstrated that immersive technologies, particularly virtual reality, can significantly enhance students' conceptual understanding of fundamental data structures and algorithms. Usability was rated highly, though the sense of presence in VR revealed design limitations. Future work will focus on refining interaction design and expanding content coverage to better bridge the gap between theory and practice while maintaining user-centered pedagogical principles. In addition, tests will be expanded to include students from other institutions with varying levels of familiarity with DSA, providing more robust data for evaluation. Incoming studies will also incorporate direct comparisons between metaverse and VR versions, as well as the inclusion of a control group, to more accurately assess the relative effectiveness of each learning approach.

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