Effectiveness of Immersive Virtual Environments in Learning 3D Transformations in Computer Graphics and Impact on Spatial Skills

by

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Trinity College Dublin, the University of Dublin, 2026

Supervisor: Michael Manzke

With the rapid advancements in virtual reality technology, new opportunities are emerging for enhancing learning experiences, particularly in disciplines that require strong spatial reasoning. However, it remains unclear to what extent immersive virtual environments can influence students' spatial skills, especially in complex subjects such as 3D transformations in computer graphics. This study explores the role of immersive virtual reality in improving spatial skills by evaluating its effectiveness in teaching 3D transformations through visual and interactive experiences.

Over the course of several studies, our research has gradually honed in on the impact of immersive virtual environments on students' understanding of spatial concepts. Initially, the focus was on user engagement and satisfaction with virtual systems. As the research progressed, it became evident that the immersive nature of virtual reality and its interactive capabilities played a crucial role in improving spatial reasoning. Through a combination of pilot studies, one-group pretest-posttest designs, and expert evaluations, this work identifies how immersive virtual systems provide significant affordances for visual learning and interaction with 3D transformations.

This thesis presents findings that suggest immersive virtual environments, by allowing students to manipulate and visualize 3D objects from multiple perspectives, enhance their spatial skills more effectively than traditional methods. Furthermore, the study investigates how expert evaluations of virtual effectiveness align with user experiences, ultimately highlighting the value of immersive virtual reality as a tool for teaching spatial reasoning in computer graphics. The results point to the potential of virtual reality not just as an educational tool but as a platform to reshape the way spatial learning is approached, particularly in STEM education.

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Abbreviations

VR Virtual Reality

AR Augmented Reality

MR Mixed Reality

XR Extended Reality

IVE Immersive Virtual Environment

CTML Cognitive Theory of Multimedia Learning

STEM Science, Technology, Engineering, and Mathematics

TUGS Universal Graphics System

HMD Head-Mounted Display

SDK Software Development Kit

Revised PSVT: R Revised Purdue Spatial Visualization Test: Visualization of Rotations

UI User Interface

GUI Graphical User Interface

Chapter 1

Introduction

Almost every area of daily life, including education, has changed in recent years because of technology. Virtual Reality (VR) is one example of an innovation that has the potential to change how students learn by increasing engagement and interaction in education. Virtual reality in teaching has already made considerable strides in some fields, including health, engineering, science and the arts. VR is expected to gain strength as technology advances and is made more widely available, benefiting both teachers and students.

The teaching of 3D transformations is a topic that is crucial to computer graphics, yet there have been few research on the topic. This concept serves as a crucial main basis for many more complex computer graphics issues and many students appear to find it challenging because it requires a wide range of abilities. In addition to the pedagogical difficulty, 3D transformations present a substantial computer science challenge. They require students to understand and apply abstract computational constructs such as matrix operations, coordinate system representations, and the precise ordering of transformation sequences, as even minor implementation errors may result in incorrect visual outputs. The need to bridge the gap between visual reasoning and programming implementation adds further complexity to mastering this topic. From a computer science perspective, this complexity lies not only in conceptual understanding but also in the accurate computational formulation and composition of transformation operations within programmable graphics systems. A lack of spatial skills is a major contributor to many learning difficulties in this area, a lot of students' misconceptions about 3D transformations appear to be caused by their incapacity to comprehend and mentally manipulate three-dimensional scenes [134, 138]. It frequently guides conflicts when facing obstacles resulting from the high level of imagination and spatial orientation required in 3D space and some students find it challenging to complete tasks in the academic context that require these skills. Spatial visualization is one of the key elements of spatial abilities, which is the capacity to handle objects in two and three dimensions mentally. There is a relationship between spatial abilities and computer graphics performance, the highest association was seen for spatial visualization skills and is important to understand the concept of 3D transformations. These skills should receive more attention in learning computer graphics because they directly affect students' performance.

A common set of challenges in learning 3D transformations involves comprehending the sequence of transformations, determining the correct rotation direction, applying appropriate scaling factors, and accurately interpreting three-dimensional visual representations. Many students face difficulties not in understanding the underlying concepts, but in effectively applying them in practice [134]. Representation is a key factor in helping learners overcome these obstacles, which has driven the creation of various interactive learning tools. For instance, the I3T framework allows learners to dynamically explore and visualize 3D transformations, demonstrating potential for enhancing comprehension [33]. Likewise, mobile-based augmented reality applications have been reported to foster learner motivation and facilitate visualization, thereby improving students' conceptual grasp of 3D transformations [137]. These findings highlight the value of integrating interactive and immersive technologies in addressing spatial reasoning difficulties and strengthening conceptual knowledge within computer graphics education.

Extended Reality (XR) technologies, encompassing virtual, augmented, and mixed reality, have emerged as effective tools for enhancing spatial learning through the provision of interactive and immersive environments [147, 31]. These technologies deliver dynamic visualizations that support conceptual comprehension and facilitate problem-solving processes, rendering them valuable across diverse educational fields such as computer graphics, emergency response training, and safety simulations [7, 5]. Empirical studies have demonstrated that XR-based instructional methods can achieve comparable outcomes to traditional pedagogical approaches in improving learners' knowledge acquisition, understanding, and overall performance [159, 55]. Within the domain of computer graphics education, various XR applications have been developed to aid the learning of 3D transformations by enabling students to more intuitively visualize and manipulate transformation sequences [136, 97, 78]. However, prior investigations have yet to specifically evaluate the impact of immersive virtual environments on spatial visualization skills to mastering 3D transformations.

VR can be used to make learning computer graphics more effective and easier by creating 3D models in an effort to enhance the student's visualization of 3D transformations. Students must have a visual awareness of the underlying processes in order to understand computer graphics concepts, and it has been suggested that immersive virtual environments is an especially useful technique for jobs requiring comprehension of 3D scenes. Non-immersive VR was the main focus of most spatial ability studies; understanding and evaluating the effectiveness of immersive VR settings for promoting the enhancement of spatial visualization skills is one of the primary areas that require more research. This is because current studies during the evaluations did not make a distinction between various abilities.

This research seeks to address this gap by designing and evaluating an immersive VR-based instructional approach for the learning of 3D transformations in computer graphics. The studies contribute by creating and empirically examining a purpose-built VR learning environment aimed at fostering spatial visualization skills within the specific context of 3D transformation concepts, through both student-based evaluations and expert assessments. The findings suggest that this kind of setting supports the improvement of spatial visualization skills among students.

1.1 Motivation

The primary motivation for this research is a recent study that revealed a relationship between spatial abilities and computer graphics performance, highlighting the necessity to further investigate spatial abilities in the context of learning computer graphics. It appears that a specific set of spatial skills may be necessary for success in computer graphics based on the correlation between the students' skills for spatial visualization and mental rotation [70]. Another motivation is students have difficulty with a number of basic concepts, including 3D transformations, in part because they lack visuospatial abilities. Spatial ability plays a major role in the topic of 3D transformations, a good level of spatial reasoning skill is thus necessary for understanding 3D transformations.

1.2 Problems

Technology integration into education is the focus of this interdisciplinary research project. The intricate process that involves the interaction of three factors—technology, pedagogy and content—makes up technology integration in learning. Virtual reality is the technology used in this study, following the cognitive theory of multimedia learning (pedagogy) in the field of computer graphics education (content). All three of these elements will be taken into account when designing. While the evaluation will take into account virtual reality's potential in terms of its influence on students' spatial abilities and conceptual understating of the topic of 3D transformations, as seen in (Figure 1.1) below.

Research issue

Given the advantages of virtual reality technology in education, as well as the persistent difficulties students face in learning 3D transformations and developing spatial skills, this study is guided by both a hypothesis and a set of research questions.

- Lack of visuospatial skills is one of the major problems in computer graphics education and learning [135, 138, 134].

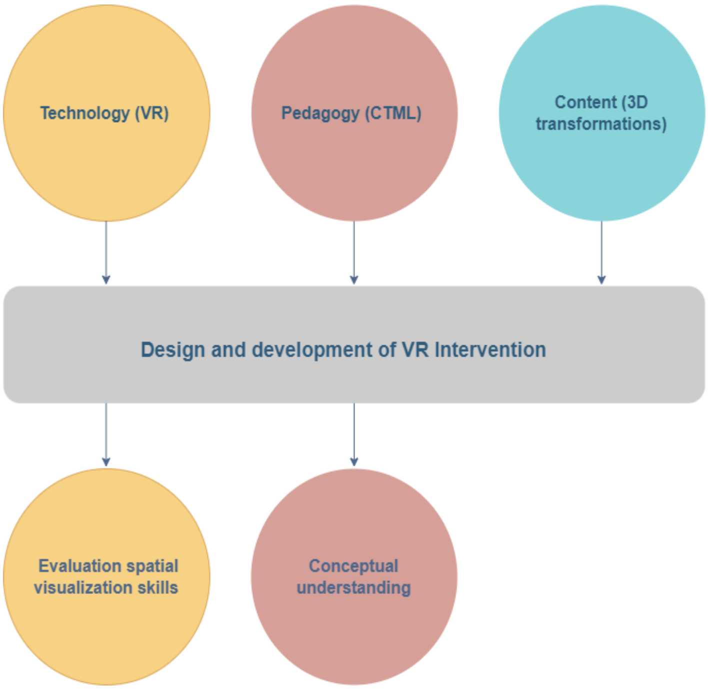


Figure 1.1: Components of the research

- Common issues and misunderstandings with 3D transformations learning among students [138, 134].
- A theoretical approach supporting the intervention when used with educational immersive VR was not mentioned in the majority of research [44], the usage of learning theory is an important factor in any educational activity or instrument.
- Different abilities are not differentiated when evaluating spatial abilities; instead, they are evaluated as a single concept [70, 93].
- There is a lack of empirical evidence on the specific contribution of IVE to both conceptual understanding and spatial visualization skill development in this domain.

1.3 Research Questions

The following is the thesis hypothesis given the advantages of virtual reality technology in the process of learning and the problems related to learning 3D transformations and spatial skills:

H1: An Immersive Virtual Environment (IVE) has a significant positive impact on students' spatial visualization skills in understanding 3D transformations in computer graphics.

From this hypothesis, the following questions serve as the foundation for this research.

RQ1: What teaching tools and methodologies are applied in computer graphics instruction, and what challenges or gaps exist in teaching and learning 3D transformations?

RQ2: How can an immersive VR learning environment be designed and developed to support visualization and manipulation of 3D transformations?

RQ3: To what extent does the IVE improve students' conceptual understanding of 3D transformations?

RQ4: How does the IVE impact students' spatial visualization skills?

RQ5: What are expert perspectives on the educational effectiveness, usability, and engagement of the VR system?

1.4 Structure of the Thesis

The research presented in this thesis is structured as eight chapters:

In Chapter 2, we review the foundational literature on computer graphics, virtual reality, spatial skills, and their relevance in education. The chapter discusses the challenges and tools used in computer graphics education, particularly focusing on 3D transformations and the difficulties students face in learning this concept. In addition, it explores the role of virtual reality and spatial skills in education.

Chapter 3 outlines the methodology of the research, including the research design, environment design, structuring of the investigation, and ethical considerations.

Chapter 4 outlines the theoretical frameworks, design principles, and development process of the immersive VR environment. The design of the immersive learning virtual environment is guided by the cognitive theory of multimedia learning was published at iLRN in 2024 [7].

Chapter 5 presents the pilot study including methodology, findings, and insights from the study, which informed refinements to the VR environment. This work published at UKICER in 2024 [6].

Chapter 6 presents the main mixed-methods study, including methodology, results, and discussion of findings. It also describes the enhanced version of the VR environment used in the study. This work was published at Eurographics 2025 [9].

Chapter 7 reports on an expert review phase, including a structured evaluation of system usability, clarity, interactivity, and pedagogical effectiveness, along with thematic analysis of open feedback. The work was published at UKICER 2025 [8].

Chapter 8 summarizes the key findings across all phases of the research, discusses limitations, and outlines directions for future research and development. An application paper consolidating this work was published at EuroXR 2025 [46].

1.5 List of Related Publications

- Alobaid M., Effectiveness of Virtual Reality in Learning 3D Transformations in Computer Graphics and Impact on Spatial Skills. Doctoral Consortium in the 18th International Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (VISIGRAPP_DC), Lisbon, Portugal, 2023. DOI: VISIGRAP.DC/23-6

- Alobaid M. and Manzke M., Can an Immersive Virtual Learning Environment

Enhance Spatial Visualization Skills in Learning 3D Transformations? Digital Education Conference, Waterford, Ireland, 2023. DOI: 10.13140/RG.2.2.31120.01288

- Alobaid, M. and Manzke, M., Work-in-Progress—Design of Immersive Virtual Reality Environment for Learning 3D Transformations. Immersive Learning Research-Academic, pp.96-102, 2024. DOI: 10.56198/U6C0WZAL1

- Alobaid M. and Manzke M., Learning 3D Transformations through an Immersive Virtual Environment for Higher Education in Computer Graphics. In Proceedings of the 2024 Conference on United Kingdom & Ireland Computing Education Research (UKICER '24). Association for Computing Machinery, 2024. DOI: 10.1145/3689535.3689542

- Alobaid M., Young G. and Manzke M., Immersive Virtual Reality for Developing Spatial Skills in Learning 3D Transformations in Computer Graphics. The Eurographics Association, 2025. DOI: 10.2312/eged.20251015

- Alobaid M. and Manzke M., Validating an Immersive Virtual Environment for Learning 3D Transformations: From Design to Student Impact to Expert Evaluation. In Proceedings of the 22nd EuroXR International Conference (EuroXR 2025) (pp. 94–97). VTT Technical Research Centre of Finland, 2025. DOI: 10.32040/2242-122X.2025.T440

- Alobaid M. and Manzke M., Expert Evaluation of a VR Tool for Learning Computer Graphics. In Proceedings of the 2025 Conference on United Kingdom & Ireland Computing Education Research (UKICER '25). Association for Computing Machinery, 2025. DOI: 10.1145/3754508.3754537

Chapter 2

Literature Review

This chapter covers the related work carried out in this area of research. The first element of problem identification involves reviewing the literature. In this section, the literature review has been conducted to examine computer graphics in further detail and look at the challenges in learning them and discuss the methods and tools that were used to teach computer graphics, problems associated with learning 3D transformations and the current state of spatial skills with computer graphics and virtual reality. Finally, virtual reality technology is discussed, including a definition, categories and potential for use in computer graphics education as well as the benefits and challenges of using VR in education.

2.1 Computer Graphics

Computer graphics, like other scientific disciplines such as mathematics, physics, and chemistry, is a field of study. The majority of computer science students consider computer graphics to be an essential course. Computer graphics is considered difficult to learn because it involves a diverse range of skills, including spatial skills, mathematics, design, problem-solving, and programming [118, 94, 135]. It can be a challenge to teach computer graphics using traditional ways. A range of approaches and systems have been presented over the last three decades to improve computer graphics teaching and learning.

2.1.1 The Challenges for Computer Graphics in Education

The common problems in the field of computer graphics teaching and learning are four main difficulties that can be categorized as listed below [135].

1. The knowledge in basic programming and mathematics is not enough especially to calculate projections, transformations and implementation.
2. Hard for students to comprehend geometric concepts like projections, transformations and 3D modeling.
3. Hard for students to solve logical problems and make a relationship between programming, theory and the result of visual effects.
4. Not many peers and teachers interact and students have become passive learners.

2.1.2 Methodologies and Tools for Teaching Computer Graphics

The methods for teaching computer graphics were divided into three groups i.e., a top-down, a bottom-up and a hybrid methodology [133, 49]. The term of top-down approach allows the use of tools to expound the content of computer graphics, enough coverage of the core ideas is provided to aid learners' future self-learning [139, 133]. On the other hand, the bottom-up approach determines the fundamental principles and building components and is usually based on textbooks, like as transformations and raster algorithms followed by a thorough examination of each component [133, 154, 124]. A combination of top-down and bottom-up approaches is referred to as a hybrid method. To support required skills and capabilities, it combines a variety of pedagogical approaches or educational technologies with clear tasks [49] and developed educational resources for graphics programming [142] and conceptual comprehension [119] to solve learning difficulties and enhance the delivery of content in computer graphics.

Conventional teaching methods in computer graphics, such as textbooks and slide presentations, rely on static 2D illustrations. These offer only limited insight, as students are unable to interact with the visuals or experiment with foundational concepts such as parameter adjustment [131, 104]. This limitation is particularly problematic for topics that inherently require three-dimensional reasoning, including geometric transformations, ray tracing, 3D modeling, illumination and shading models. Without opportunities for interactive exploration, students struggle to develop the deep visual and conceptual understanding needed to master these areas [118]. As a result, computer graphics has long been recognized as one of the most difficult subjects to teach in computer science education.

To address these challenges, several teaching strategies and tools have been proposed. It has been suggested that an effective approach to teaching graphics fundamentals is to expose students to the complete graphics pipeline, including modeling, viewing, and rendering stages [25]. Complementary research has focused on lowering technical barriers through the use of pre-structured templates, which minimize or even eliminate the need for extensive programming, thereby enabling students to concentrate on conceptual understanding rather than the syntactic complexity of graphics APIs [155].

Technological developments have also significantly influenced how computer graphics is taught. In the early 2000s, the emergence of affordable, specialized Graphics Processing Units (GPUs) transformed the field by enabling home computers to render increasingly complex and photorealistic scenes. This leap in computational capability coincided with the growing ubiquity of computer-generated imagery (CGI), leading to growing interest in computer graphics education. During this period, several Java-based tools emerged including GL4Java, JOGL and Java3D, gained popularity as accessible tools for teaching 3D graphics. These implementations offered scene-graph abstractions and Java bindings for OpenGL. Over time, WebGL has largely supplanted these earlier tools.

Since around 2010, the availability of devices capable of supporting 3D graphics has increased substantially. The introduction of OpenGL ES 3.0, which forms the basis for WebGL 2.0, allowed high-performance 3D rendering not only on desktop computers but also on mobile devices and web browsers. This technological expansion coincided with the explosive growth of mobile gaming, which by 2017 surpassed both PC and console gaming in market share. The launch of the first consumer VR headset, the Oculus Rift, in 2016, catalyzed the growth of augmented and virtual reality applications.

A detailed review of the tools used in computer graphics education will be reviewed. During the early 1990s, the Universal Graphics System (TUGS) was introduced computer graphics educational tool, designed to support the teaching and learning of fundamental graphics concepts. TUGS has demonstrated that it is an effective and valuable tool for teaching computer graphics. The ideal method for teaching computer graphics, according to the authors, is to have students create a "graphics pipeline" that is support modelling, viewing, and rendering activities. Students, on the other hand, will only see the final pictures when the whole pipeline was done. TUGS is a module-based rendering system that allows students to replace specific components of the system with their own implementations while still producing images utilizing the remaining capabilities. It is said to improve students' comprehension of computer graphics fundamentals [25].

Tutorial, developed by Papper and Gigante, is an interactive exploratory learning environment designed to help programmers understand graphics programming and the Graphics Library (GL) from Silicon Graphics Inc [99]. Four demo programs are used to guide the student through the tutorial, each of which presents simulated source code. It is used by the student to run each line of code and observe the consequences on the graphical state, representations of internal hardware and final result. By selecting fragments of the source code, directly modifying parameters, and watching the effect on the produced image, the student can investigate the effect of the different functions of the graphics library.

Early research on teaching computer graphics emphasized the benefits of interactive and visual learning. Schweitzer developed visualization tools to illustrate 2D/3D transformations, perspective projections and colour spaces, allowing students to predict the effects of parameter changes [117]. Naiman extended this approach with interactive modules covering like window and viewports, color manipulation and 2D transformations, implemented in C with the GL library; these modules combined GUIs with pseudocode tracing to help students understand algorithms and enabled self-paced learning [94].Other work in the mid-1990s addressed challenges such as limited lab resources and the misconception that graphics was "easy" because of its visual nature, proposing interactive multimedia tools for computer graphics with animations and images to walk students step by step through algorithmic processes, reduce instructor workload, and encourage cognitive engagement [106]. Later work developed fully web-based courses that integrated lectures, illustrative examples, programming activities, and a 3D application builder that supported the creation of visual content without requiring coding effort [59].

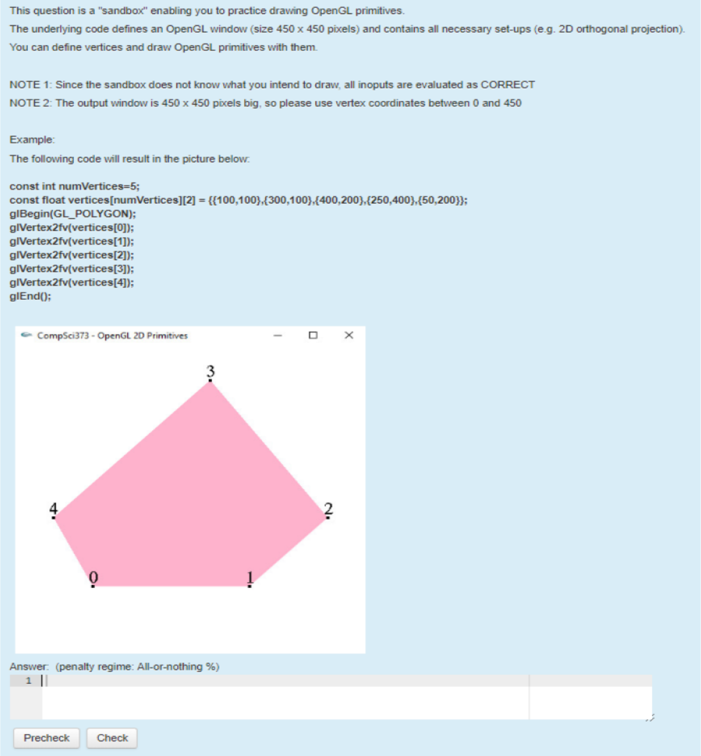
In the early 2000s, a variety of interactive tools were developed to improve accessibility and engagement in computer graphics education. The Java/GL4Java web-based tutorials enabled students to explore rendering concepts directly in a browser by adjusting the parameters of the OpenGL functions and immediately visualizing the effects, eliminating the need for specialized installations [157]. Game-inspired software was also introduced, where learners applied graphics concepts to complete tasks, such as rebuilding virtual objects and answering questions, thereby promoting active and problem-based learning [14].

Several tools such as Graphicsmentor and SIECG focused on providing immediate visual feedback [95, 36, 40]. These tools typically employed graphical interfaces to manipulate transformations, camera settings and lighting making abstract computer graphics concepts more intuitive. Some systems offer optional code input [36, 40], while others deliberately avoid exposing the underlying graphic code [95] to lower the learning curve for beginners.

Other approaches emphasized constructivist learning by using rapid prototyping environments [140], enabling students to interactively configure and experiment with different stages of the graphics pipeline. Distributed and collaborative system [105] was also proposed, supporting code sharing, joint rendering, and real-time communication, extending learning beyond the classroom. Pedagogical graphics engines [104] and simplified scripting languages [131] were introduced to balance interactivity with programmability. Graphics engines enabled classroom demonstrations with real-time student interaction and supported cross-platform development. Simplified scripting allowed learners to define transformations and animations through GUIs or the SDL pseudocode interface, with automatic conversion to OpenGL, making it easier and faster to learn and create graphics.

A top-down approach to teaching computer graphics was supported by two Java-based tools: one for learning Java 3D and practicing transformations through interactive scene graphs, and another simplified game engine built on Java 3D that emphasizes clarity and correctness over optimization, enabling students to use a single programming language across the course [143]. The Graphics Teaching Tool (GTT) is a Java applet that integrates 2D/3D graphics, designed to help non-technical students visualize the graphics pipeline. Users can create scenes using 2D/3D geometry and raster images, while built-in "data inspection tools" allow them to examine and adjust transformations and other scene attributes [129].

In 2011, a set of web-based tools was developed to support the teaching of computer graphics concepts, such as morphing and shading. Each tool was stand-alone, requiring no additional materials, and evaluations indicated improvements in exam performance as well as enhanced student perceptions of concept clarity [120]. CodeRunnerGL is a browser-based tool developed to enhance the teaching and assessment of computer graphics [156]. It allows students to write, run, and test OpenGL code interactively within an integrated environment. By combining code execution with real-time visualization, the tool provides instant feedback, enabling students to learn graphics concepts more effectively through practical experimentation. Its interactive sandbox-style environment encourages hands-on practice, allowing learners to apply theoretical knowledge and explore graphics programming in a supportive and engaging way (see Figure 2.1).



This question is a "sandbox" enabling you to practice drawing OpenGL primitives.

The underlying code defines an OpenGL window (size 450 x 450 pixels) and contains all necessary set-ups (e.g. 2D orthogonal projection).

You can define vertices and draw OpenGL primitives with them.

NOTE 1: Since the sandbox does not know what you intend to draw, all inoputs are evaluated as CORRECT

NOTE 2: The output window is 450 x 450 pixels big, so please use vertex coordinates between 0 and 450

Example:

The following code will result in the picture below:

```
const int numVertices=5;
const float vertices[numVertices][2] = {{100,100},{300,100},{400,200},{250,400},{50,200}};
glBegin(GL_POLYGON);
glVertex2fv(vertices[0]);
glVertex2fv(vertices[1]);
glVertex2fv(vertices[2]);
glVertex2fv(vertices[3]);
glVertex2fv(vertices[4]);
glEnd();
```

Answer: (penalty regime: All-or-nothing %)

Figure 2.1: An example of CodeRunner sandbox for testing OpenGL primitives [156]

There is also a VR platform in computer graphics, which allows the display of slides of a PDF presentation in a scene's static content. It can display 3D objects with the capability of writing or drawing on the surface of a 3D model or in space, as shown in Figure 2.2. A virtual framework is used in an immersive learning polygonal mesh processing course and for the purpose of enhancing the teaching of subjects that require visualization and 3D imagination. It was also tested in a small sample of students by two male and two female students enrolled in this course [48].

RePiX VR is a virtual reality tool designed to teach the fundamentals of the rendering pipeline [45]. Their approach emphasizes making abstract processes such as transformations, rasterization, lighting and more tangible through interactive and embodied visualizations. The system integrates learning analytics to track learner interactions. The evaluation indicates that even novices can effectively grasp computer graphics fundamentals using VR. While their work focuses on the rendering pipeline, it demonstrates how VR can effectively support the teaching of difficult abstract computer graphics concepts.

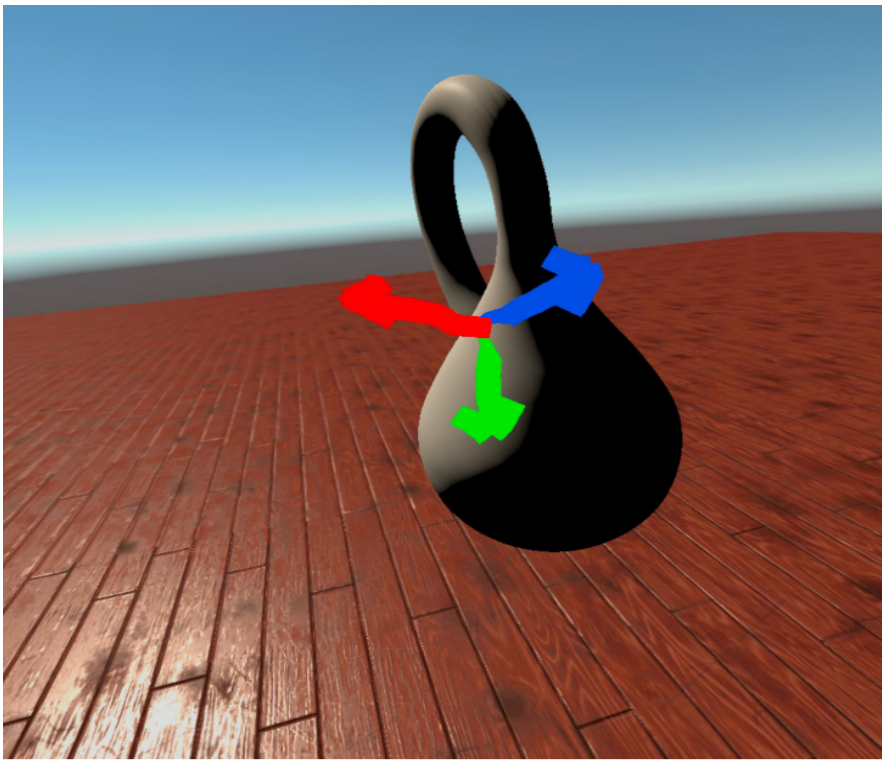


Figure 2.2: Screenshot of a painting function applied on an object [48]

Summary and Limitations of Existing Approaches

The previous section reviewed a wide range of methodologies, tools, and technological developments aimed at improving computer graphics education. These approaches have significantly enhanced accessibility, interactivity, and engagement through programming support, visual feedback, web-based environments, and immersive technologies. To clearly highlight the limitations of prior methods in relation to 3D transformation learning, Table 2.1 summarizes representative approaches and identifies the key gaps relevant to this research.

Table 2.1 presents selected representative examples rather than a complete list of all discussed tools. As illustrated in the table, although prior systems have advanced various aspects of visualization and interaction, they typically address visualization, programming, or immersion as separate instructional components rather than integrating them into a unified learning framework. In particular, structured support for 3D transformation sequencing remains limited, especially in immersive environments. Furthermore, the systematic development and assessment of spatial visualization skills

Approach	Primary Focus	Limitation in 3D Transformation Learning
TUGS	Graphics pipeline construction and modular experimentation	Emphasizes incremental pipeline implementation; does not target structured transformation sequencing or spatial visualization skill development
Tutorial	Step-by-step code execution with graphical feedback	Emphasizes programming execution; limited structured support for visual reasoning and mental simulation of transformation effects
Graphicsmentor	Immediate visual feedback for transformations and lighting	Provides interactive manipulation but offers limited linkage between transformation concepts and their underlying algorithmic implementation
Web-based Tools	Accessible browser-based visualization and parameter experimentation	Non-immersive tools that provide limited structured guidance for 3D transformation sequencing and no focus on spatial visualization skill development
CodeRunnerGL	Integrated coding environment with real-time 3D visualization	Supports programming–visual linkage and matrix-based feedback; lacks explicit focus on spatial visualization development or immersive interaction
Mobile AR Applications	Real-world object manipulation with interactive visual feedback	Enhances visualization and transformation animation but provides limited embodied interaction and spatial visualization skill assessment
RePiX VR	Immersive visualization of rendering processes and graphics concepts	Focuses primarily on rendering pipeline concepts; provides limited explicit emphasis on 3D transformation sequencing and systematic spatial visualization assessment

Table 2.1: Computer graphics teaching approaches and limitations in 3D transformation learning

are rarely embedded within these tools. While some platforms partially connect visual outputs with code execution, few provide a coherent framework that simultaneously supports embodied interaction, structured transformation learning, and the cognitive processes underlying spatial reasoning.

These limitations indicate the need for an instructional approach that integrates immersive interaction with structured transformation sequencing and targeted spatial visualization development, thereby bridging visual reasoning and programming implementation in computer graphics education.

2.1.3 3D Transformations in Computer Graphics

Many introductory courses in computer graphics include 3D transformations as a fundamental concept [13], and they are employed in modelling, texturing, view transformations, and rendering processes. One major problem in computer graphics learning and teaching is that 3D transformations are challenging topics. Many students lack the ability to interpret representations of 3D transformations and to create mental images of their effects [134]. This often leads to difficulties when facing tasks that require a high level of imagination and spatial orientation in 3D space. Consequently, some students struggle to complete academic tasks that depend on these skills. Studies have shown that common misunderstandings in 3D transformations include difficulties visualizing rotations, limited understanding of certain primitive transformations, and confusion regarding the sequence of transformations [138, 134]. This concept serves as a crucial basis for many more complex issues, and the evidence indicates that a significant number of students struggle with it. However, very few studies have investigated this topic.

For example, the I3T system integrates interactive computer graphics into the teaching of geometric transformations, enabling students to manipulate objects and immediately visualize the effects of matrix operations such as translation, rotation and scaling[33]. This approach was shown to enhance conceptual understanding by linking symbolic mathematical operations with dynamic visual feedback.

The mobile AR applications are designed to facilitate 3D transformations by allowing learners to directly manipulate objects and apply transformation operations with immediate visual feedback in real-world space. This approach has been shown to enhance students' understanding of 3D transformations, support visualization of 3D objects, and increase motivation through interactive learning [137].

Construct3D is an example of a collaborative augmented reality environment built on the mobile AR platform Studierstube, enabling multiple users to share a virtual space. It is a dual-hand 3D interaction tool that facilitates easier manipulation of 3D objects. The system is designed for mathematics and geometry education, aiming to enhance spatial abilities and support transfer of learning [57, 56]. Reports suggest that Construct3D is easy to use, encourages exploratory geometric construction, and may improve learners' spatial skills.

Despite the clear benefits of interactive technologies, their effectiveness is often limited by current technological constraints and the absence of fully embodied interaction, which is crucial for developing a strong spatial understanding. The current desktop-based learning and AR tools do not allow learners to physically manipulate 3D transformation sequences, highlighting the need for immersive solutions that can fill this gap.

3D Transformation Difficulties

Students often struggle with 3D transformations, particularly when questions involve visual representations or OpenGL code [138]. These difficulties are linked to the need for strong spatial reasoning, which is essential for understanding 3D scenes and transformations [107] and has been associated with success in computing and other STEM fields [100, 19, 76]. Success in introductory computer graphics is related to spatial visualization and mental rotation skills, highlighting a learning gap for students with limited spatial abilities [69]. Spatial ability plays a major role in the topic of 3D transformations; a good level of spatial reasoning skill is thus necessary for understanding 3D transformations.

2.2 Virtual Reality

Milgram, who first proposed the Reality-Virtuality (RV) continuum in 1994, did so to processing of the mixed reality concept. Mixed Reality (MR) is the term used to describe the area between the two worlds where the virtual and the real world are combined. The continuum includes Augmented Virtuality (AV), which is closer to the virtual world than Augmented Reality (AR), and AR, which is closer to the real world (see Figure 2.3) [91].

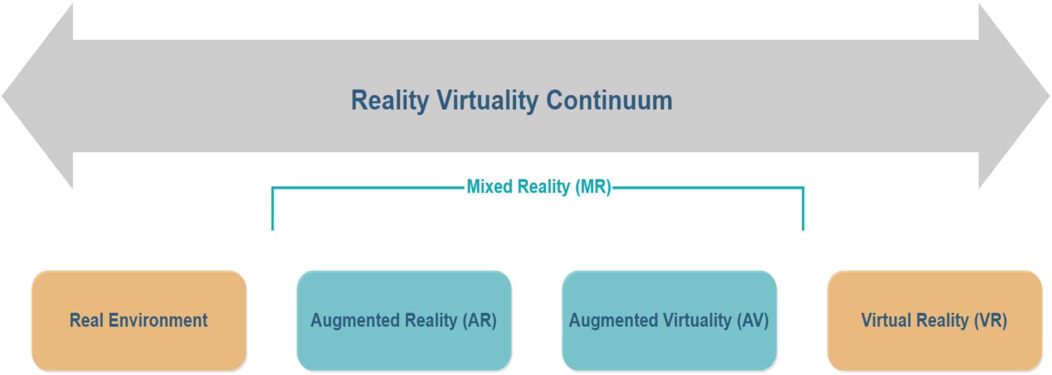


Figure 2.3: Milgrams Reality Virtuality Continuum [91]

AR, MR and VR are only a few of the more recent, immersive technologies that fall under the general concept of XR. AR is defined as the creation of 3D visualizations in the real world that users can interact with virtual objects in real-time [50]. The integration of the physical and digital worlds to create new worlds and visualizations is known as MR. The physical items here coexist with digital and engage in real-time interaction [15]. VR is a term used to describe an entire simulated reality that has been created utilizing computer technologies. This other reality must be constructed and visualized using hardware and software that can produce a convincing immersive experience. for instance, VR headsets or specialty glasses with 3D software [80]. The definition of VR is "Virtual Reality mostly can be defined as virtual object in virtual Environment" [61]. However, McCloy and Stone defined VR as "Virtual reality is best described as a collection of technologies that allow people to interact efficiently with 3D computerised databases in real time using their natural senses and skills"

[83]. Another definition is ”a combination of high-end computing, human-computer interfaces, graphics, sensor technology and networking which allows the user to become immersed in, interact, and experience in real time a three-dimensional (3D) artificial environment representing realistic or other situations” [90].

VR technology provides a learning environment that is more focused and free from outside distractions by creating a highly immersive experience. since the user is totally engrossed in the virtual setting and completely blocked out of the real world.

2.2.1 Categories of Virtual Reality

Depending on the level of immersion and the kinds of elements used in the system, virtual reality technologies are divided into three main categories: non-immersive, semi-immersive, and immersive [111]. The definition of immersive VR is a technology that gives users the feeling of being fully immersed in an environment that has been created by a computer. The user is totally cut off from the actual world in completely immersive virtual settings [123], which is the maximum of immersion and it uses a Head Mounted Display (HMD) to show 3D images. Users can access a partially digital world with semi-immersive VR, in which the virtual environment that is being shown is applied to the actual real surroundings [10]. Non-immersive VR enables users to interact with a 3D environment created by a computer while still being conscious of and in control of their actual settings which among others, is the least immersive and expensive.

2.2.2 Presence and Immersion in Virtual Reality

In 1992, the idea of presence became a topic relevant to VR. Sheridan indicated that it may be utilized in a virtual setting as a unique instance of teleoperation where the remote site is a virtual one as opposed to a physical one. He defined virtual presence as the ”sense of being physically present with visual, auditory or force displays generated by a computer” [125]. In the context of virtual reality, presence and immersion are essential concepts. The feeling of being present in a virtual environment is known as presence and the concept of immersion is user involvement in a VR experience that puts them in a state of flow. The technical features of a VR system are objectively described by the term "immersion," which indicates the level of information that may be generated in a virtual environment, while the user's psychological reaction to the surroundings is described by presence [16]. Immersion is primarily focused on the technological aspects of the VR system.

Spatial Presence

The larger concept of presence utilized in virtual reality includes a spatial presence in addition to other types of presence. The term "spatial presence" describes the fictitious impression of physical presence in a virtual setting. It emphasizes the individual's notion of being actually present in the virtual environment, their mobility and capacity to interact there, and their general sensation of "being there" [58]. The idea describes the user's subjective experience of physically being in a virtual setting as if their body and mind had been transported there. It means considering the virtual world to be an area where the user may move around and interact. An example is exploring a virtual museum in a VR headset. Users can look around and browse the virtual galleries as if they were actually in the museum.

2.3 Virtual Reality in Education

In the 1960s, the term VR was first introduced and initial usage of VR were mainly found in the entertainment sector [132]. The idea of using VR as a teaching tool, which can significantly boost the learning content's attractiveness and students' motivation to learn, didn't become popular until the 1980s.

Virtual reality is thought to play a critical role in changing higher education teaching and learning. Students' attention can surely be improved by the novelty of the experience and total absorption in a virtual world [127]. Students have been able to explore complicated subjects in methods that classic pedagogical practices cannot, thanks to high-fidelity graphics and immersive content delivered via HMD [44].

VR can provide users with unique perspectives that are hard to replicate in reality when used in cognitive learning tasks that need a high level of spatial knowledge and imagery. According to prior studies, activities of cognitive learning that need a high level of visualization and sensory comprehension are best supported by virtual technologies. More immersive content that drives multi-sensory engagement, according to researchers, can result in more effective learning results [153].

It has been demonstrated that using virtual reality as a tool has many advantages, including enhancing long-term memory retention, improving subject comprehension and boosting student motivation [102]. Although there are various examples of virtual environments that have resulted in improved learning results [44]. Other scientific areas that need conceptual or abstract thinking could advantage of VR's visualization capabilities [44].

There was a learning benefit in trials that supplemented or combined traditional learning with VR learning, which is encouraging [44]. This shows that VR could be used to enhance and complement classroom-based learning as a sort of mixed or multimodal learning [38]. It be proven to have a measurable advantage over traditional education techniques in improving students' performance.

2.3.1 The Evidence of Benefits of Virtual Reality in Education

A body of practical and experimental studies demonstrating the positive advantages of VR in education was uncovered during the review. In this study, virtual reality was used to teach a data structure course to bachelor's degree students in computer science engineering, with a concentration on sorting algorithms. Students have been taught about sorting algorithms like insertion sort, selection sort, bubble sort, and merge sort, which is initially difficult to grasp. In order to assess performance, two groups of students were formed to evaluate the VR system. One group used a virtual reality system in addition to materials of standard teaching, whereas the other used solely traditional materials. The results showed that students who utilized the VR system did better on the exam and the virtual reality system combined with traditional teaching methods outperformed the control group, indicating that the VR system has a beneficial influence on performance[1].

Several virtual reality simulators that are completely immersive were created specifically for this study that used as study stimuli. Four studies were used to evaluate virtual reality, between-media(non-immersive and immersive) and within-media (audio, text and overlay) comparisons were set up for each of these studies with students at Copenhagen University. A pre-test was used in every study to assess prior knowledge, demographic characteristics of the participants were collected and a post-test was used to assess learning outcomes. The study found that content that was naturally more tied to immersive media's affordances had better understanding outcomes than information that did not presume such traits [12]. However, when the information was presented on a Desktop instead of the virtual condition in this study, students learned more but reported feeling more present and engaged with the VR environment [75].

The simulation was designed to support biology learning and investigated the consequences of transferring a science simulation from a low-immersion virtual experience (also known as the PC condition) to a fully immersive virtual experience (also known as the VR condition). It was not intuitive to use the control panel in the virtual reality environment, the participants had to use the control panel on the side of the HMD to simulate the clicking function to choose the objects they want to manipulate, so the fact that the type of the VR headset used in this investigation was a limitation and the learner may be overwhelmed and distracted by immersive VR and experience noticeably more cognitive load according to the EEG measurement. This investigation was to assess how immersive VR compared to a desktop slideshow in terms of educational value as media for teaching in biology [102]. Students who used an immersive VR reported considerably better interest, engagement and motivation levels compared to slideshow students but they performed much lower. In VR, simulation was continuing and not under the learner's control and this could have been happened for the reason that the learner still be processing past knowledge when new data is offered, which adds an essential load to the processing of the learner and this affected the results of the study. In contrast to the slideshow, which was a short instruction under the learner's control which reduced the learner's necessary processing during the lecture.

One study was to examine the potential for teaching geometric solids in math to primary school students utilizing AR and VR technology to compare it with instructional methods that rely on books. The VR environment (see Figure 2.4) and AR environment as shown in Figure 2.5. The findings show that, in comparison to conventional teaching techniques, the use of new technologies in education, such as AR and VR, improves engagement and student interest in math instruction [30]. Using an HMD allows a VR user to become completely immersed in a 3D scene. System characteristics replace sensory information from the real environment with digital data to achieve visual immersion. This is in support of developing mental representations of the learned material. In a training setting, increased visual immersion and presence leads to better results [96]. Spatial presence is the term used to describe the individual experience of being in a real space, such as inside a virtual world. Being present impacts a student's enjoyment and motivation, which raises perceptions of learning satisfaction and quality and mediates the relationship between presence and the learning outcome [74]. This study assessed the VR experience gameplay and usability and indicated that employing immersive VR improves the quality of learning [96]. Another study found that content that was naturally more tied to immersive media's affordances had better understanding outcomes than information that did not presume such traits [12].

2.3.2 Challenges of Virtual Reality in Education

Although a large number of research show that using a virtual environment is effective and achieved better educational results, VR has been demonstrated to have a negative impact in some research [44]. In practice, this may indicate that before beginning experimental investigations, participants will need to necessitate longer familiarization trials or unrestricted navigation to avoid potential issues created by new technology. Areas in which future studies should be improved are the technological knowledge of the use of virtual reality and the theoretical approach that has been used in research. First, due to a lack of familiarity with the technology, the novelty of immersive VR

Figure 2.4: Screenshot of the activity in the VR environment [30]

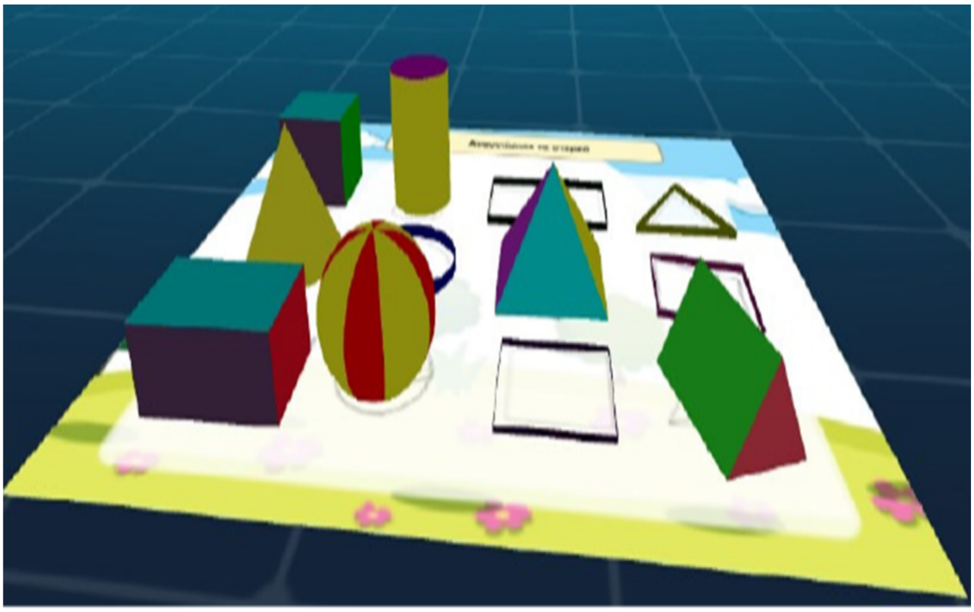


Figure 2.5: Screenshot of the activity in AR environment [30]

may hinder the outcomes of learning [4]. As a result, it's critical to include a time of extended familiarization or free exploration to help ease this problem. In addition, qualitative research like focus groups or interviews could assist researchers in better understanding the phenomenology (or actual experience) of utilizing immersive VR, as well as worries about unfamiliarity and technical fear. The usage of educational paradigms or learning theory should be an important factor in any educational activity or instrument. Theories should serve as the educational framework and basis for developing effective interventions. A theoretical approach to the intervention was not mentioned in the majority of research [44].

2.4 Virtual Reality in Psychology

The use of digital worlds in psychology has several advantages since the brain processes movements in the virtual world and the resulting perceptual alterations in a manner that is largely analogous to those of movements in analogous actual space [37]. According to conventional criteria for evaluating cognitive mapping, it was discovered that virtual environment training is almost as effective as actual exploration for the creation of cognitive "maps" of environments in many participant groups [37]. An essential part of a system that depends on automatic physiological reactions is the sense of presence generated by virtual reality. According to some researchers, significant emotional and physical reactions are produced in virtual environments that are comparable to those in real-world examinations, proving the usefulness of this media for psychological evaluation [112].

2.4.1 Depth Perception

In virtual reality educational environments, depth perception is an important component. Our eyes' ability for depth perception enables us to distinguish between the relative sizes of objects in space by allowing us to see them in three dimensions. It plays a critical role in how we connect with the outside world and can greatly improve learning outcomes in virtual settings. Studies on the perception of lightness and 3D optical illusions were successfully conducted using virtual reality technologies. Through the use of these techniques, it was possible to recreate in-depth illusions and build intricate, 3D scenes with precise control over the parameters [85]. The outcomes of this study demonstrated that the student's ability to use virtual reality programs improved their ability to perceive space. Students used virtual reality to practice tasks involving space perception and to develop better space perception [126]. Users who have depth perception may accurately perceive the relative positions and distances of things in a virtual world. For many learning scenarios, including those in engineering, architecture, and other professions that demand accurate spatial awareness, this improved spatial knowledge is essential. A study confirmed that an immersive system enhances users' spatial comprehension of the virtual model [98]. The study examined how users perceived space when utilising an immersive platform as opposed to a traditional workstation. Results showed that employing the immersive environment improved users' overall perception of the virtual model's spatial layout[98].

Depth Perception in Learning 3D Transformations

Understanding 3D transformations in immersive VR is based on the concept that immersive settings offer a more intuitive and natural approach for people to interact with and comprehend 3D spatial relationships. The main reasons that support this claim are immersion and depth perception, in which users always wear head-mounted displays in immersive environments, which track their head motions and modify the content being displayed accordingly. The user feels as though the virtual environment is all around them and reacts to their movements similarly to the way the actual world does, which gives the user an experience of depth of perception and immersion. Due to the ability to rely on their innate sense of depth perception, participants in this immersive experience may find it simple to perceive and comprehend 3D spatial relationships. Immersive settings usually enable users to interact in real-time with the virtual environment by reaching out and grasping objects or directly manipulating them, which is a form of physical interaction. Because it corresponds with our daily knowledge of moving objects in space, this concrete engagement can improve our understanding of 3D transformations.

2.5 Spatial Skills

The term ”spatial skills” serves as an umbrella that stands for a collection of related skills, including the ability to manipulate information in our minds about the objects in our surroundings and the places we live [149]. Without even being aware of it, people use spatial abilities in a variety of ways every day. From navigating through congested streets to putting furniture together, These abilities are necessary for perceiving and managing the things and spaces in our surroundings. For instance, people must consider the available space and the distance from the curb when parking a car on a street side. Our ability to seamlessly engage with the actual world depends on our spatial skills. The definition of spatial skill is “the ability to generate, retain, retrieve, and transform well-structured visual images” [71]. The ability to conceptualize three-dimensional objects and make inferences about them is referred to as spatial intelligence [70]. Spatial intelligence is also known as spatial reasoning skills, visuospatial skills, or spatial skills. For more than a century, spatial abilities have been the focus of extensive investigation; they constitute a significant area of educational and cognitive psychology study. According to those who specialize in the study of human intelligence, our intelligence is still not unique and is made up of a variety of various elements. All theories and research conducted in this area agree that one factor that makes up intelligence is strongly associated with our spatial and visual abilities because they help us mentally perceive 2D and 3D environments and make it easier to solve spatial issues, whether actual or imagined [41]. One of the key aspects of human intelligence is spatial ability [141] and it is particularly significant for a number of professions or training and educational programs [32]. Computer science, mathematics, and architecture are just a few of the disciplines that require spatial abilities. Due to the importance of human intellect and cognitive capacities to academic success, these topics have become more prominent in research [70].

2.5.1 Spatial Abilities Classifications

Linn & Petersen suggested that there are three types of spatial ability through a meta-analysis of the literature on the subject covering the years 1974 to 1985 [68]. These categories are spatial perception, mental rotation, and spatial visualization.

- **Spatial visualization skill** the capacity for manipulating and comprehending spatial relationships and 2D/ 3D objects in the mind. It includes mentally visualizing, manipulating, and rotating various objects. With the use of this ability, people may build and manipulate objects in their minds, as well as comprehend their orientations and sense the relationships between them. An illustration would be to mentally visualize and rotate a 3D cube.

- **Spatial perception skill** is the capacity for accurate perception and interpretation of spatial relationships. It means being conscious of and comprehending how objects in the external environment are related spatially in terms of sizes, distances, and perspectives. Navigation, distance estimation, pattern recognition, and comprehension of the relative places of objects are all possible with the use of spatial perception. For instance, estimating an object's size based on how it looks.

- **Mental rotation skill** refers to the capacity to rotate two and three-dimensions objects in space mentally. When deciding if two items are identical but have different orientations, one must mentally rotate the object in consideration.

2.5.2 How to Measure Spatial Skills

The tests that are used to measure these abilities are frequently the best sources of understanding. Since there is no test that can measure spatial reasoning as a whole, its aspects are used to make an assessment of spatial intelligence. In order to provide accurate information regarding the many sub-components of spatial intelligence, various particular standardized tests are used. It is crucial for researchers to be aware of the element they wish to evaluate in order to choose the appropriate tests that have a strong record of validity and reliability in line with their research goals. For the purpose of measuring different components of spatial ability, many tests have been developed. The following lists a few of the more well-known examples of these tests. In 1976 Guay created the Purdue Spatial Visualization Test (PSVT:R) and the Purdue Spatial Visualization Test is a 3D mental rotational test that is primarily used to look at the relationship between engineering students' academic success and their spatial skills in the ability of spatial visualization. Vandenberg and Kuse mental rotations test[150] is also an additional test for assessing mental rotations, it was created in 1978 based on the geometries of Metzler and Shepard[88]. The Revised Purdue Spatial Visualization Test (Revised PSVT:R) is an improved test of (PSVT:R) [158]. There are also different assessments that evaluate the skill for visualizing, such as tests that require mental cutting[145]. Various paper folding examinations that require the test taker to determine how a folded piece of paper will appear when unfolded after having holes punched through it [121, 63].

2.5.3 Differences in Gender

In the discipline of spatial reasoning skills field, studies on gender-related differences in spatial skills and the causes of these differences continue to be a controversial issue. Previous research has shown that everyone has different spatial abilities. Researchers have proposed various explanations for this phenomenon, including social variables, toys and games from childhood, hormonal changes, and the frequency and type of regularly played video games, playing musical instruments, sports activities and gender differences [89, 22, 23, 47]. In tests of spatial rotations under time pressure, men typically perform better than women. The majority of males actually do better on computer-based assessments than those that are administered using paper and pencil. While there may not be a difference in the performance between the sexes in some visualization tasks, there may be differences in approaches to solving problems in spatial [149]. However, some researchers argue that there is either no or very few gender differences in spatial visualization skills [63].

2.6 Learning and Importance of Spatial Skill

Each technical and scientific domain is impacted by spatial abilities [79], skills in spatial reasoning have been linked to success in STEM fields like computing [100, 19, 76]. The improvement of spatial skills has received a lot of attention, a study found that even a slight gain in spatial ability can greatly increase students' achievement in learning [20]. There are some studies that show success is correlated with having high spatial abilities [52, 53]. Using causal data from STEM fields and a variety of connections observed across different computer domains, this is sufficient evidence to imply that improving spatial skills may improve learners' computing performance [101]. The fact that some types of spatial ability are better performance predictors than others may have a range of impacts on computer science education because we are aware that spatial development might enhance overall computing abilities [26, 101, 128]. Unlike many other forms of intelligence, spatial skills may be developed, which can lead to better academic results. For instance, Lowrie et al. noticed that developing students' spatial skills in primary school increased maths results by roughly 10% [72]. The reason for this is that in order to comprehend the knowledge in STEM courses, students must be able to cognitively construct and manipulate spatial data utilizing their spatial skills [67].

2.6.1 Spatial Skills on Computer Graphics

Computer graphics include a wide range of skills including programming, math, problem-solving and spatial abilities. A recent study provided strong evidence for a correlation between spatial skills and performance in computer graphics [70]. A certain set of spatial skills may be necessary for success in computer graphics, according to the correlation with students' abilities in spatial visualization and mental rotation [70]. The highest association was seen for spatial visualization skills and no spatial perception association was found in this study. By studying 3D geometric transformations that need the ability to mentally manipulate 3D objects and coordinate systems, computer graphics directly affect students' visual-spatial abilities [42]. Prior studies have shown that spatial abilities can be improved [73, 149]. The researchers believe that students studying computer graphics will greatly benefit from improving spatial abilities [70].

Spatial Visualizations Skills in Computer Graphics

To comprehend 3D transformations, there is need to mentally manipulate items in any position and be knowledgeable about representational techniques, which closely relate to the idea of spatial abilities. It is also necessary to develop one's spatial visualizations to enhance learning. For the thses reasons, spatial visualization ability is crucial in computer graphics, especially when it comes to learning 3D transformations.

- Understanding spatial relationships: Three-dimensional objects can be translated, rotated, and scaled as a result of 3D transformations. Those that possess spatial visualization abilities are able to comprehend the spatial connections between items, visualize them accurately in their positions and directions, and understand how these changes to the scene as a whole are affected by these changes.

- 3D model creation and manipulation: For the effective creation and manipulation of 3D objects, spatial visualization abilities are essential. To acquire the correct forms, sizes, and arrangements, learners must mentally manipulate models in three dimensions. Using spatial visualization abilities enables one to precisely scale, rotate, and position items.

- Problem-solving and debugging: Implementing 3D transforms might be difficult for learners when studying computer graphics. Good spatial visualization abilities enable one to mentally break down and evaluate the 3D environment or object, identifying and resolving problems with transformations. They are capable of visualizing the desired result, contrasting it with the actual outcomes, and making corrections as necessary.

- Controlling the camera and scene composition: Creating scenes and using virtual cameras in 3D environments requires the ability to spatially visualize space. Positioning things, arranging to light, and choosing camera perspectives and angles are all necessary when creating a scene. They can decide where to place objects based on their knowledge of spatial visualization, and they can change camera settings to get the right composition by mentally seeing the layout of the scene.

In general, spatial visualization abilities are crucial for learners to understand computer graphics' 3D transformations because they help with understanding spatial relationships, controlling the camera and scene composition, problem-solving, 3D model creation and manipulation. For students to succeed in their education in computer graphics, it is essential that they develop and improve these abilities.

2.7 Spatial Skills with Virtual Reality

The term "digital media" refers to all forms of digital learning materials, primarily virtual and augmented reality systems. The most important component in improving visualization abilities is an instructional method or digital media. A means for improving user visualization of intricate 3D objects and environments are provided by virtual reality (VR) technologies. The dimensional relationships of shown objects are easier for users to perceive via experience and interaction with the environment [92]. The experimental virtual environments can help participants the improvement of spatial perception skills [93]. Spatial presence is one of the benefits of virtual immersive environments [115]. Spatial ability and spatial presence are related, and an individual's spatial presence in virtual immersive environments differs from the actual world [27]. People who engage in virtual immersion environments often feel more present and their attitudes tend to improve [144]. Active glasses were only employed in a small number of research investigations to simulate the effect of immersion. Mixed reality and immersive VR have begun to be employed in some medical research for the training of surgeons, however, the majority of these research do not aim to measure the effects of using VR or AR for spatial improvements [146].

2.7.1 Spatial Navigation

Human navigational performance has been demonstrated to be impacted by spatial orienting skills and video game experience. The influence of video gaming experience is particularly noticeable when navigating virtual environments such as the mazes employed in this study [2].

2.7.2 Learning with VR and Importance of Spatial Skill

The correlation between academic success and spatial skill is controversial in VR learning. Despite the fact that certain research have successfully confirmed the highly beneficial impacts of spatial skill on academic performance [87, 66], other studies have been unable to confirm similar results [62, 21]. The ability-as-compensator hypothesis can account for the unexpectedly small impacts [17, 132]. The theory states that learners with poor spatial skills receive the greatest benefit from external educational resources because these resources make up for their weak spatial skills [17]. Learning with using VR, poor spatial ability learners gain more from VR's benefits than do high spatial ability learners. Due to the fact that VR allows poor spatial ability learners to effectively create a mental image of the learning data through the use of explicit and external representations [17], this hypothesis is not always supported. These features facilitate the processing of spatial data and reduce the cognitive load for people with weak spatial skills in order for these students to process learning material with higher working memory and ultimately do better in their academic studies [64]. The enhancer hypothesis states that learners with excellent spatial skills benefit more from VR in education due to their excellent cognitive capacity and resources necessary to create a mental image of the learning material in a VR environment [67].

2.7.3 Immersive and Non-immersive Virtual Environments

Non-immersive VR was the main focus of most spatial ability studies, little study has been done on immersive VR. The absence of research on spatial skill in immersive VR learning creates a research gap where it is unclear whether spatial visualization would be improved in an immersive VR environment. The importance of understanding how immersive VR affects students' spatial visualization.

Schnabel and Kvan used computer screens and immersive virtual environments to compare how people perceive and comprehend spatial volumes. Participants who studied in an immersive VR environment understood the volume and its parts in three dimensions more clearly [116]. In this study, the researchers used non-immersive VR and AR educational software which simulates the game-based activity of orienteering in engineering graphics to test the improvement of spatial skills. The findings showed that training exercises increased the spatial ability's component parts like spatial visualization, mental rotation and spatial orientation. It can support the improvement of spatial skills necessary for various engineering problem-solving techniques. It was shown that neither before nor after the training exercise, there were any differences in spatial skill levels between men and women [113]. Another study makes use of a desktop VR environment. Students from secondary schools were divided into three groups for the study: a control group, an interactive treatment group, and an animation treatment group. Every group used the same exercise sets to train. The interactive group used software that allowed them to interact with the items while the animation group mainly saw animations of the exercises. Finally, the control group learned using the traditional pencil and paper training methods. According to the findings, every student improved to some extent in every treatment group. More specifically, the interactive group's students, both male and female, displayed the greatest improvement gains, whereas those in the animation group improved somewhat and those in the conventional group improved poorly. Male students generally made more progress than female students, with the interactive group showing the greatest gender difference in gains. However, regardless of the technique utilized, female students improved less than male students in all groups [110]. In one investigation, the experiment was conducted out by a group of University of Alicante Multimedia Engineering students. Participats were instructed to use a virtual reality program or computer screen which is specially designed educational activity as part of the trial to evaluate if the students' spatial abilities could be improved. A virtual reality learning activity is designed that can help students develop their spatial abilities by displaying and manipulating some basic polyhedral shapes. The experiment participants were split into two groups: an experimental group and a control group to perform the same learning task except the interface device used. All of the students took a spatial visualization test twice: once before starting the activities and again after completing them. The experimental group's spatial skills improved as a result of the VR learning activities, according to the test findings.The study's fundamental limitation is that it used a low-cost technique that provided a lower immersion sense when compared to more expensive alternatives [93].

Sun et al examine how learners with various levels of spatial skills respond to VR-based learning and its effects on their cognitive loads compared with the traditional learning environment [132]. In VR, learning performance was found to be dramatically improved in low spatial learners, who also had significantly lower cognitive loads. Due to their high cognitive loads in a traditional learning setting, students with low spatial abilities often struggle to build cognitive models on their own. They therefore get more from a VR-based experience [132].

2.8 Summary

This chapter started with an examination of methodologies and teaching tools that are applied in computer graphics and the challenges associated with teaching and learning computer graphics. However, very few research have look into the issue of 3D transformations learning in computer graphics. This concept serves as a crucial main basis for many more complex issues, many students struggle with this subject and the cause of many problems in learning is impeded by a lack of spatial skills. In a number of academic fields, there is growing interest in using virtual reality technology.

The advantages and difficulties of employing VR technology are being explored and studied by many academics. They consider that among the most promising modern technologies for enhancing students' learning and enhancing their spatial skills is virtual reality. Given the literature described above, we may conclude that students' spatial skills have a significant impact on learning across a wide range of disciplines, and that in the context of virtual reality-assisted instruction, spatial abilities are another crucial element that are frequently discussed. Non-immersive VR was the main focus of most spatial ability studies [64, 86, 21, 110], little study has been done on immersive VR [93, 132]. Understanding and evaluating the effectiveness of immersive VR settings for promoting the enhancement of spatial visualization skills is one of the primary areas that require more research. This is because current studies during assessments did not make a distinction between various abilities. When creating educational content for this media, take into account the unique benefits of immersive virtual reality for learning. The manner in which spatial skills are evaluated and developed must be carefully considered. For instance, it has been found that many papers only utilize one particular test. This may not accurately reflect students' overall spatial skills, which could lead to inaccurate findings when examining the relationship between academic performance and spatial skills in certain topics. Test kits that cover all spatial skills should ideally be used to measure spatial abilities. But in a classroom setting, this is frequently not possible because it might take a lot of time. The results should be interpreted with greater caution if shorter, more focused tests are performed. In light of these gaps, this study aims to develop students' spatial visualization abilities and enhance the learning of 3D transformations through an immersive solution.

Chapter 3

Methodology

3.1 Introduction

This chapter outlines the research methodology employed to assess the effectiveness of an immersive VR environment in facilitating the learning of 3D transformations within computer graphics. This research was conducted to address challenges in teaching and learning three-dimensional transformations. As discussed in the literature review, students frequently struggle with visualizing transformations and connecting graphical manipulations with the underlying programming concepts [138]. These difficulties are closely related to spatial visualization skills, which are critical for understanding transformations yet are not adequately supported by traditional teaching approaches.

In response to these challenges, this study examined the use of an IVE as an alternative teaching and learning approach. The central hypothesis was that an immersive environment could provide learners with meaningful opportunities to interact directly with 3D objects, experience transformations dynamically, and receive immediate feedback, thereby strengthening both their conceptual understanding and spatial reasoning skills. Based on this hypothesis, a set of research questions was developed in Chapter 1, which guided the design, implementation and evaluation of the study.

3.2 Research Design

The research used a multiphase mixed methods design [108] to systematically answer the research questions. This design involves conducting multiple studies over time, utilizing both quantitative and qualitative data, with each phase building on the results of the previous ones. This approach is particularly suitable for the iterative development and evaluation of an educational intervention such as a VR-based learning tool to give a richer and more reliable understanding of the effectiveness of the system. The three studies were linked as follows:

1. A pilot study to assess usability, initial user experience, and feasibility of the VR environment before large-scale deployment with students.
2. A main student study to examine the effect of the IVE on students' spatial visualization skills and conceptual understanding of 3D transformations.
3. An expert validation survey to collect feedback from experts on the educational value, usability, and interactivity of the VR-based environment.

This structured approach allowed the research to progress in a systematic and coherent manner, moving from the development and testing of the VR environment, to the evaluation of its impact on learning, and ultimately to validation through expert assessment.

3.3 Environment Design

The IVE was designed to support both the visualization and manipulation of 3D transformations, directly addressing challenges identified in prior research. Unlike many previous studies, which focused on technology without explicit theoretical grounding [44], this environment was developed using a theoretical framework to ensure educational effectiveness.

The cognitive theory of multimedia learning was selected as the guiding theoretical framework because it explains how learners process and integrate information presented through different modes. The study of 3D transformations requires engagement with both visual and spatial representations, such as observing objects being rotated, scaled or translated and symbolic representations for example, OpenGL code and transformation parameters. The theory provides a principles for designing instructional materials that supports learning without overloading cognitive capacity.

By applying this theory, the environment was designed to present information in multiple forms that visual demonstrations supported by text and code representations—to ensure that learners could connect transformations with the programming commands that implement them. The system provided immediate interactive feedback, which reduced cognitive load and reinforced the connection between actions and results. In this way, students actively engaged with the multimedia content of the environment, encouraging appropriate cognitive processing and thereby fostering meaningful learning.

3.4 Structuring the Investigation

The research was conducted in three complementary phases, each serving a specific purpose in evaluating the immersive VR environment.

3.4.1 Pilot Study

The pilot study was conducted to confirm that users' initial experience allowed them to navigate the environment effectively and interact with its features without encountering significant barriers. Insights from this phase informed refinements to the interface design and visual feedback. By addressing these issues early, the study ensured that subsequent evaluations focused on learning outcomes rather than being influenced by usability limitations.

3.4.2 Main Study

The main study evaluated the extent to which the IVE improved students' conceptual understanding of 3D transformations and enhanced their spatial visualization skills. Pre- and post-tests were administered to measure gains in spatial ability, while a knowledge test assessed conceptual understanding. In addition, post-study surveys captured students' experiences with the VR learning environment. This study directly addressed the central hypothesis by examining whether the IVE could strengthen spatial visualization skills and improve understanding of 3D transformations in computer graphics.

3.4.3 Expert Survey

To complement the student-focused evaluation, an expert survey was conducted to assess the educational effectiveness and usability of the IVE from a professional perspective. Experts in computer education, software engineering, virtual reality and human-computer interaction reviewed the environment, providing feedback on educational effectiveness, usability, interactivity and engagement, and . This phase provided external validation of the system and ensured that the findings could inform broader applications in teaching 3D transformations.

Table 3.1, summarizes the three studies, their purpose, sample size, data types and instruments.

This methodology ensured that each study was based on the previous, with feedback and results guiding the subsequent phase, while also generating robust evidence of the educational effectiveness of the VR environment.

3.5 Ethical Considerations

All studies received ethical approval from the Research Ethics Committee (REC) of the college. Participants were informed about the nature and purpose of the study, signed informed consent forms, and were assured of the confidentiality and anonymity

Phase	Purpose	Sample Size	Data Types	Instruments
Pilot Study	Test usability and identify initial issues	7	Mixed (quant + qual)	Custom questionnaire
Main Study	Evaluate the tool's impact on learning and spatial skills	49	Mixed (quant + qual)	Demographic questionnaire, pre/post spatial ability test, knowledge test, post-survey
Expert Survey	Confirm appropriateness and value from an expert perspective	16	Mixed (quant + qual)	Expert evaluation survey

Table 3.1: Overview of the research studies

of their data. Participation was voluntary and participants could withdraw at any time without consequences. The approval reference numbers were as follows: Pilot study (3029), main study (2854), and expert survey (24-0805).

3.6 Ensuring Quality and Rigor

Several strategies were applied to ensure the quality of the research. Quantitative reliability was strengthened through the use of standardized tests and internal consistency checks. A systematic thematic analysis process supported qualitative trustworthiness, carried out in a step-by-step manner and refined through peer discussion to confirm the accuracy of interpretations. Triangulation was achieved by integrating multiple methods, data sources, and participant groups, thereby reducing potential bias and enhancing the validity of the findings. Finally, transparency was maintained by carefully documenting methodological decisions and openly acknowledging the limitations of the system.

3.7 Summary

This chapter outlines the methodological framework guiding the research in evaluating the VR environment. We employed a multiphase mixed-methods design, integrating three studies a pilot study, a main study, and an expert validation study. The VR environment was designed using a theoretical framework, combining interactive visualizations and symbolic representations to support meaningful learning while minimizing cognitive load. Ethical considerations and quality assurance measures were also addressed.

Chapter 4

Design and Development

4.1 Introduction

This chapter outlines the design and development of the virtual reality-based learning environment intended to support the learning of 3D transformations. The environment was developed to address common challenges faced by students in understanding abstract 3D concepts using traditional two-dimensional instructional methods. By providing a spatial and interactive platform, the VR environment aims to enhance the understanding of key transformations by learners, including translation, rotation, and scaling, and to improve their spatial visualization skills, which is a crucial element in computer graphics education.

The instructional design of the virtual immersive environment is grounded Mayer's Cognitive Theory of Multimedia Learning (CTML). The VR environment integrates CTML principles to reduce cognitive overload, promote active engagement, and optimize visual information processing. These principles were embedded in various design choices, such as minimizing extraneous content, synchronizing text with visual animations, and allowing learners to interact directly with 3D objects.

This chapter presents the theoretical frameworks that guided the design of the VR environment, outlines the design objectives, explains how CTML principles were applied, and describes the structure and technical development of the learning environment, laying the groundwork for the studies presented in the subsequent chapters.

4.2 Theoretical Frameworks

Any learning instrument or activity must have a theoretical or paradigmatic foundation in order to be effective. Theories explaining how pupils absorb, process, and retain knowledge can be broadly categorized as learning theories [44]. These theories ought to give educators a pedagogical approach and a basis for designing better interventions when used in conjunction with educational immersive VR. The pedagogical framework guiding the design of the VR intervention in this research is based on Dr. Richard Mayer's Cognitive Theory of Multimedia Learning (CTML), which describes how people process multimedia messages, and is applied in the design of the virtual environment (see Figure 4.1). The fundamental concept of this theory is that having access to multiple forms of media helps pupils learn better and actively select the information that is most pertinent to their learning, arranging it into mental or cognitive representations and then combining them with what they already know. In brief, people learn through multimedia when they generate mental representations from images (like photos, illustrations, video, or animation) and words (like printed or spoken text) to incorporate new information into existing knowledge after processing it. By doing this, the possibility that the knowledge will be stored in long-term memory is improved [160]. Cognitive load theory plays a significant role in Mayer's cognitive theory of multimedia learning. The basic idea of the theory is that depending on the type of information we receive during the process of learning, it leads to one of three various kinds of processing that occur in the brain. The table below lists the types of cognitive load that students face in the learning process (see Table 4.1). And to lead the learner's appropriate cognitive operations without overloading their working memory, instructional designers must overcome these challenges [81]. In light of the fact that our ability for real-time information processing is limited, to ensure the greatest possible retention in long-term memory, the goal for educators should be to create multimedia that controls essential processing, and optimizes generative processing while minimizing extraneous processing. Therefore, while Mayer's ideas offer guidance on how to create multimedia learning messages that are effective, each translates to the best practice for managing the cognitive load [81].

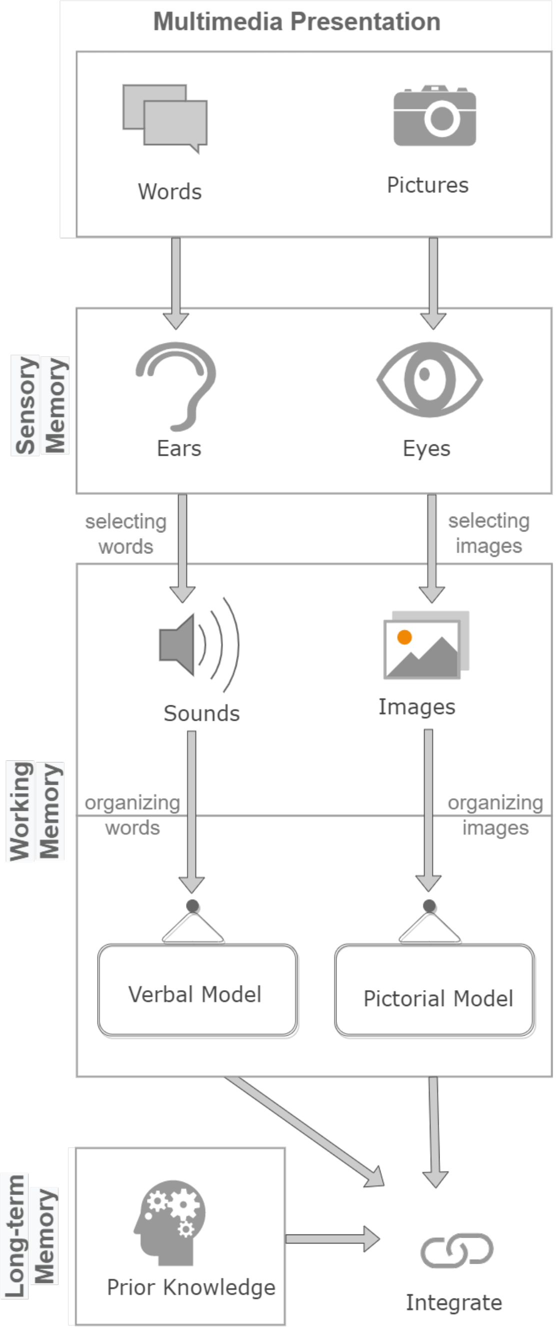


Figure 4.1: Cognitive theory of multimedia learning (CTML) [81]

Name	Description	Caused By	Learning Processes
Extraneous Processing (Extraneous Load)	Cognitive processing that does not support learning because it diverts attention away from essential material	Poor instructional design	None
Essential Processing (Intrinsic Load)	Cognitive processing required to mentally represent and understand the core content in working memory	The inherent complexity of the content	Selecting relevant information
Generative Processing (Germane Load)	Cognitive processing used to construct and integrate new knowledge with prior knowledge for deeper understanding	The learner's motivation	Organizing and integrating information

Table 4.1: Three types of cognitive load [81]

4.3 Design Objectives

The design of the immersive virtual learning environment was driven by the goal of addressing spatial reasoning barriers that are often encountered by students in computer graphics education. Traditional methods, such as textbook illustrations and 2D software, are often limited in the ability of students to internalize complex 3D transformation concepts. Immersive virtual environments offer a promising solution by providing depth perception, stereoscopic vision, and real-time motion tracking, allowing students to physically engage with transformation concepts [51, 98]. These features improve the ability of learners to perceive spatial relationships, helping them better understand the effects of transformations and enhance their problem-solving performance [134, 60].

The design and development process was directed by the following pedagogical and instructional objectives:

- **Enhance conceptual understanding of 3D transformations:** By enabling students to interact directly with 3D objects and apply transformations such as translation, rotation, and scaling, the VR environment aims to provide a learning experience that facilitates deeper comprehension of abstract concepts in 3D space.

- **Promote spatial visualization skills:** Through the immersive nature of virtual environments, learners can engage in real-time interaction with 3D transformations, improving their ability to mentally manipulate and visualize objects in space.

- **Reduce cognitive load and increase learning efficiency:** The immersive environment incorporates multimodal feedback aligned with CTML [7, 34]. This multimodal feedback helps manage the cognitive load by presenting information in a way that minimizes extraneous cognitive demands, thus improving learning effectiveness and participation.

- **Increase student engagement and motivation:** VR environments have been shown to increase student engagement, making the learning experience more enjoyable and motivating [34]. By immersing students in interactive, real-time environments, the VR system aims to create a dynamic learning environment that holds the attention of the learners and maintains their interest over time.

- **Improve problem-solving performance:** By offering a hands-on immersive experience with 3D transformations, the VR environment is designed to enhance students' ability to solve spatial problems and apply learned concepts to practical tasks, improving their performance in tasks requiring spatial reasoning.

These objectives provided the foundation for the instructional design and development of the VR system. The following section will describe how CTML was applied to ensure that VR content aligns with these learning goals while adhering to pedagogical best practices.

4.4 Application of CTML Principles

The development of the immersive VR learning environment was informed by Mayer's CTML [81], in conjunction with the intended instructional objectives and the capabilities of immersive VR technologies. This conceptual framework enabled the development of a meaningful VR experience for learning 3D transformations in computer graphics, supporting effective cognitive processing by controlling intrinsic load, reducing extraneous load, and optimizing germane load.

According to CTML, meaningful learning occurs when learners engage in appropriate cognitive processing, which is encouraged by well-structured multimedia content. The VR environment was developed to align with this model by integrating visual cues and embodied interaction elements in a manner that supports cognitive efficiency and engagement. In the following, we outline how specific CTML principles were applied in the instructional design of the VR experience.

4.4.1 Modality Principle

Learning is improved when learners receive information through both visual and auditory channels. In our VR environment, this principle was implemented by providing visual demonstrations of 3D transformations using interactive 3D shapes, accompanied by textual explanations for transformation functions and OpenGL commands. For example, when users scale a cube in the VR scene, they receive real-time visual feedback, helping them grasp transformation concepts through immediate, observable results. Moreover, the modality principle's boundary conditions refer to situations in which the effectiveness of spoken narration may vary depending on factors such as content complexity, technical terminology, and the need for precise symbolic representation. In such cases, printed text may be more effective than spoken narration for content that involves technical terms and symbols [82].

4.4.2 Segmenting Principle

The segmenting principle states that learning is improved when information is presented in user-controlled segments. To manage intrinsic load and support comprehension, the content was divided into modular segments, each focusing on a specific type of transformation (translation, rotation, or scaling). Within each module, users progressed through clearly structured activities—for example, rotating around a single axis or moving objects along specific directions—allowing them to focus on one concept at a time. VR controllers were used to navigate between modules, giving learners control over pacing and sequence.

4.4.3 Pre-training Principle

The design of the VR environment was guided by the pre-training principle, which emphasizes introducing learners to essential concepts and tools before engaging with tasks. To support this, an initial tutorial was included to familiarize users with the interface and VR controls. This pre-training phase helped reduce extraneous cognitive load by enabling learners to identify and understand core components early on, allowing them to concentrate on mastering tasks and interaction within the immersive space.

4.4.4 Coherence Principle

To minimize extraneous cognitive load, the VR interface was designed with simplicity and clarity in mind. The controls were kept intuitive, and only information essential to the learning goals was presented. Unnecessary visual elements and interface clutter were removed. For instance, transformation tasks were paired with straightforward, brief annotations and clean visuals, ensuring that learners remain focused on key concepts.

4.4.5 Spatial Contiguity Principle

Textual and visual elements were presented in close spatial proximity to reinforce the connection between action and result. For example, when users selected a translation function, the corresponding OpenGL translation command and visual feedback were shown near the transformed object. This design supports learners in connecting the visual effects of transformations with the instructional content, reducing the need for mental bridging.

4.4.6 Redundancy Principle

In alignment with the redundancy principle, we avoided presenting identical spoken and written content simultaneously. However, in areas requiring reinforcement of abstract concepts, such as understanding 3D transformation functions and corresponding OpenGL syntax, textual explanations were intentionally paired with visuals. This redundancy provided multiple entry points for learners to comprehend the material, especially for technical tasks.

4.4.7 Temporal Contiguity Principle

The synchronized delivery of textual information with visual transformations helped reinforce temporal contiguity. For example, as users rotated a rectangle in the VR environment, they received real-time feedback showing the axis of rotation, the applied angle, and the corresponding OpenGL rotation command. This temporal alignment ensured that learners could immediately connect instructional content with visual outcomes, thus reducing the extraneous cognitive load.

4.4.8 Multimedia Principle

Throughout the VR environment, learners received multimodal feedback through visual responses to objects and textual displays of the applied OpenGL commands. This feedback supported embodied interaction by allowing learners to connect their physical actions with transformation outcomes, reinforcing learning objectives and enhancing their perception of understanding to optimize germane load.

4.4.9 Personalization Principle

The personalization principle from CTML typically emphasizes the use of conversational language; however, in this context, immersive interactivity functioned as a form of personalization by allowing learners to construct understanding through direct manipulation and immediate feedback. Simple, friendly printed text within the VR scene further enhanced approachability and learner engagement.

We developed an immersive learning environment that promotes an understanding of 3D transformations by integrating CTML principles into the instructional design of the VR system. Through the alignment of multimedia content, interactive controls, and cognitive load management, learners can explore technical elements such as OpenGL commands and visual principles in a clear and engaging virtual environment.

4.5 Design of the Immersive VR Environment

We investigated the 3D transformation concepts that learners found most difficult to understand in . The literature review indicates that although most students had a conceptual understanding of simple transformations, they often omitted important information. The result of a study showed that misunderstandings in 3D transformations were in the rotation direction, lacking understanding of some cases in primitive transformations [138]. These common problems occur while students are trying to answer a question [138]. Students find it difficult to understand questions that contain visual representations and OpenGL codes. The possible reason is that having strong spatial abilities is necessary to comprehend 3D scenes and transformations [107]. The representations of 3D transformation issues are perceived as being challenging and requiring more spatial reasoning [134]. A good level of spatial visualization skill is thus necessary for understanding 3D transformation.

The immersive VR environment was designed to facilitate the learning of 3D transformations in computer graphics, with a specific focus on enhancing learners' spatial visualization skills. The environment is structured into a series of learning modules, each one focusing on a specific kind of transformation. These modules enable learners to practice and observe their effects in real-time. Through this hands-on interaction, learners are encouraged to explore, test hypotheses, and receive immediate visual feedback, reinforcing their understanding and supporting learning.

From a system perspective, the primary use cases include: (1) selecting an object within the 3D Cartesian space, (2) applying a specific transformation function (translation, rotation, or scaling), (3) entering or adjusting transformation values along the X, Y, and Z axes, and (4) observing the real-time visual and symbolic feedback generated by the system. These use cases are designed to support active learning through direct manipulation and embodied interaction.

In the early development of our VR environment, we aimed to create an immersive platform that enables users to apply various types of 3D transformations within a 3D Cartesian coordinate system. These transformations include translation, rotation, and scaling. User interaction within the VR environment is facilitated through VR controllers, which serve as the primary interface for navigating and manipulating objects. Upon entering the scene, users are presented with a control panel that allows them to select an object and choose a transform function (see Figure 4.2).

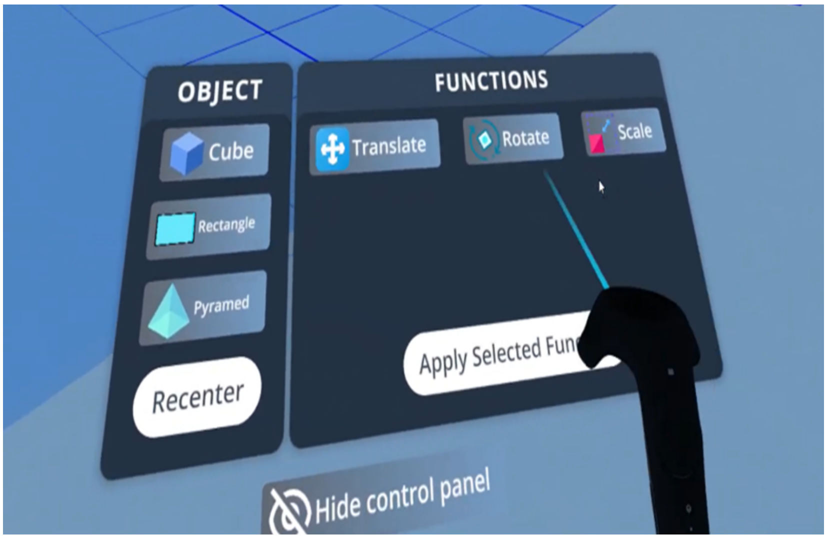


Figure 4.2: Objects and functions

This control panel provides options for entering specific X, Y, and Z values for the transformation or selecting preset values. Real-time feedback is a crucial aspect of the user experience, and our VR environment instantly reflects applied transformations within the scene. Users can observe the effects of their actions as objects undergo transformations, allowing immediate visual feedback and validation of the desired outcome. These affordances, such as direct object manipulation, real-time system response, spatial mobility, and synchronized display of OpenGL commands, enable learners to connect abstract computational operations with concrete visual outcomes.

This design directly aligns with Mayer's CTML by supporting generative processing through active organization and integration of visual and symbolic information.

Furthermore, to enhance understanding and visualization of transformations, each object shape within the scene is labeled with a colour and its face name. This labeling scheme provides users with clear visual cues regarding the identity and orientation of objects as they transform. The labeling and visual cues also reduce extraneous cognitive load by minimizing ambiguity and helping learners quickly identify reference points during transformations, thereby supporting efficient essential processing.

The VR environment also supports user mobility, allowing them to walk and explore the virtual space freely. Users can move their heads around to view objects from different angles, enhancing their spatial awareness and understanding of the scene. Additionally, users have the option to walk using VR controllers, providing them with greater control and flexibility in navigating the environment. This embodied navigation serves as an affordance for strengthening spatial encoding processes and encourages generative processing, as learners actively integrate spatial perspectives with transformation logic.

To aid in comprehension of transformations, 3D projections of objects in the system plane enable users to visualize how objects are transformed relative to the coordinate system. In addition to addressing challenges related to interpreting visual representations and understanding OpenGL code, the scene presents an object alongside its corresponding transformation function and OpenGL command. This integration provides users with insight into the underlying rendering processes, supporting a clearer understanding of the transformations being applied (see Figure 4.3). By integrating visual, spatial, and symbolic representations within the same interaction space, the system operationalizes the multimedia and spatial contiguity principles of CTML, ensuring that learners do not need to mentally integrate separated sources of information.

In general, the developed VR environment offers a comprehensive and intuitive platform for applying and visualizing basic 3D transformations, enabling users to gain deeper insight into the spatial manipulation of objects within the scene.

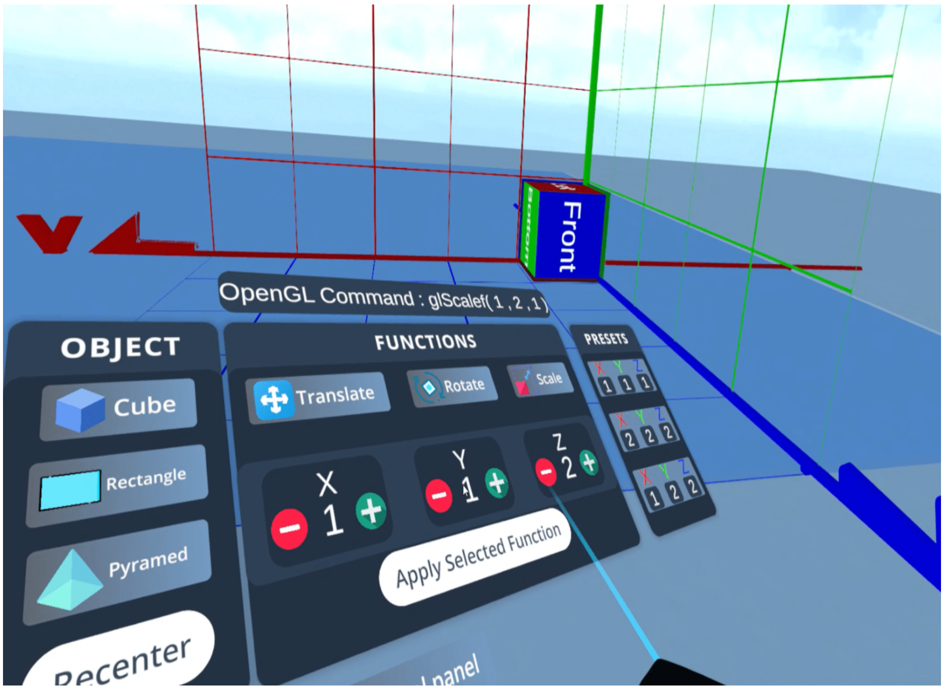


Figure 4.3: First development of the environment

4.5.1 Technology Specification

There are no set standards for the technology employed for teaching computer graphics, which is likely a result of the individual teachers' preferences and personal experiences, similar to how there are differences in technology used to instruct different computer curriculum courses. In Chapter 2, we looked at the state of the art in current technology to help education. We are interested in investigating and constructing a VR environment since it allows for a detailed examination of spatial relationships, which supports the development of 3D representations and scenes. To clarify how learners interact with the environment and how they consider information, we construct questions about how the environment is perceived.

Development Environment

When selecting a development kit, there are many options accessible. We looked at the following key factors to determine which Software Development Kit (SDK) would work best for this project:

1. **Cost:** Free VR SDKs are what we intend to use.

2. **Platforms:** We aim to design the environment for Windows, some VR SDKs support this through native runtimes such as SteamVR's OpenXR runtime.

3. **Hardware Components:** The HMD that will be used is the HTC Vive Pro, which is a fully immersive virtual reality headset.

4. **Unity Support:** The Unity game engine that can be used to create a VR environment with C# as the programming language.

We need to be clear about why we chose to utilize Unity for this research before we go into the SDKs. Virtual reality programming is supported by Unity and gives developers access to extensive documentation. With less need for a powerful PC setup, developers can now design complicated projects for low-end devices. For this research, Unity is a better choice. We used the Unity engine's most recent version, Unity 2022.3.24f1, at this time in the study. For use with the HTC Vive headset, there are many VR SDKs available and most work with Unity. OpenXR is a free and open standard SDK and API designed to be compatible with a wide range of XR devices and platforms, including HTC Vive through SteamVR's OpenXR runtime. OpenXR provides developers with the flexibility to create applications that run seamlessly across different hardware and software environments, making it a forward-looking choice for cross-platform XR development and integration with Unity.

Hardware Specifications

The HTC Vive headset requires a computer operating on Windows 7 or a later version to support the OpenXR runtime during the development phase. For optimal performance within a virtual reality environment, the system should meet the following minimum hardware requirements: at least 4 GB of RAM; an Intel Core i5-4590 or AMD FX 8350 processor (or equivalent); an NVIDIA GeForce GTX 970 or AMD Radeon R9 290 graphics card (or equivalent); available USB ports for connecting the headset, controllers, and related peripherals; and an HDMI or DisplayPort interface for video output.

4.6 Summary

This chapter outlined the design and development of the immersive VR environment for teaching 3D transformations in computer graphics. Guided by CTML, the system was structured to reduce cognitive load, integrate visual and textual representations, and provide interactive tasks with real-time feedback, applying CTML principles throughout the design. Developed in Unity with OpenXR, the environment enabled learners to manipulate 3D objects while simultaneously observing visual outcomes and the corresponding OpenGL code, effectively bridging abstract concepts with practical visualization. In summary, it demonstrates how the theory-driven design and development have resulted in a purpose-built VR tool that addresses the challenges of learning 3D transformations and provides a foundation for empirical evaluation in future studies.

Chapter 5

Pilot Study

5.1 Introduction

The initial phase of the research was the pilot study, conducted after the design and development of the first version of the immersive VR environment to learn 3D transformations, based on CTML.

The study evaluates usability and user experience, as well as perceptions of spatial understanding within the environment, to identify technical or instructional design issues before conducting the main study. This was an essential part of improving the environment, and the results provided insight into how well participants navigated the VR environment, their overall satisfaction, identified challenges or limitations within the VR setting, perceived benefits and recommendations for improving the usability and user experience overall.

The next sections describe the methodology including participant, instrument, and data collection, followed by the result derived from both quantitative and qualitative feedback.

5.2 Methodology

This pilot study used a mixed-methods approach to evaluate the prototype of immersive virtual environment design to learn 3D transformations in computer graphics, integrating quantitative and qualitative data to improve the design and the environments' usability and interactivity.

The study was conducted to evaluate the environment in terms of perceptions, usability, satisfaction, engagement, and suggestions for improvement in learning through the immersive virtual experience. Participants had good prior experience in VR and computer graphics. They were first introduced to the virtual environment, where the purpose of the pilot study was explained. Participants were informed that the aim was to test the functionality, usability, and clarity of the system. They were explicitly instructed to explore the environment thoroughly and to try as many functions as possible, including translation, rotation, scaling, navigation, and interface controls, to identify potential usability issues or technical errors. They were encouraged to test different combinations of transformations to detect any problems. After this introduction, they completed a post-questionnaire.

The collected responses were coded and analyzed using SPSS. For the study, the descriptive, validity and reliability assessment have been completed. The internal consistency metric Cronbach's alpha was computed to evaluate the reliability of the evaluation instrument. Due to the small sample size, statistical analyses for construct validity were not performed. Instead, content and face validity were ensured through the involvement of subject-matter experts, who reviewed the questionnaire to confirm that it covered relevant aspects of the construct.

The analysis included both descriptive statistics and thematic analysis, examining participants' perceptions of ease of use, satisfaction, engagement within the virtual reality environment, and suggestions for improvement. This mixed-methods approach integrated data from the Likert-scale items with qualitative insights from open-ended responses.

5.2.1 Participants

A small group of seven participants (5 male and 2 female) from the Graphics and Vision group at Trinity College Dublin was recruited to assess the initial design. All participants had expert experience in VR and computer graphics and were actively working in related research or development, ensuring a high level of familiarity with immersive systems, 3D transformation concepts, and graphics programming.

The selection of this expert population was intentional, as the pilot study aimed to obtain technically informed feedback on system functionality, interaction logic, visual clarity, and potential implementation limitations. Participants were expected to critically evaluate the accuracy of transformation operations, the correctness of the visual representation of 3D transformations in VR, and the clarity of the relationship between these transformations and the corresponding OpenGL commands displayed in the interface. In addition, it was expected that they would provide detailed and technically grounded suggestions to improve usability and instructional design before testing the system with students in the main study.

5.2.2 Instruments and Data Collection

A custom-designed post-use questionnaire was administered to collect feedback from participants. It included 14 Likert-scale items assessing usability, perception of 3D orientation and movement, and overall satisfaction and engagement, along with 5 open-ended questions to capture qualitative feedback on recommended usage time, difficulties encountered, factors affecting engagement, and suggestions for improvement. Participants were first introduced to the virtual environment and allowed to interact with it freely. After exploring the system, they completed the questionnaire. They were given unrestricted access to the environment during the study.

5.2.3 Pilot Training Session

The pilot training session focused on evaluating the usability and functionality of the immersive VR environment. After being informed about the purpose of the pilot study, participants were instructed to explore the system thoroughly and interact with all available features. They selected geometric objects and applied transformation functions, including translation, rotation, and scaling. Participants experimented with different values along the X, Y, and Z axes and tested various combinations and sequences of transformations to identify potential inconsistencies or technical issues. They also explored navigation features and interface controls to evaluate clarity and ease of use. This structured exploratory process allowed participants to assess the system comprehensively and identify areas requiring refinement before the main study.

5.3 Results

5.3.1 Reliability and Validity

The internal consistency of the evaluation instrument was assessed using Cronbach's alpha, which yielded a reliability coefficient of 0.876, indicating good reliability among the 14 items in the questionnaire, as shown in Table 5.1. Due to the small number of participants, statistical analyzes of construct validity were not performed. Instead, content and face validity were ensured through expert review: domain experts evaluated the questions for clarity, relevance, and coverage of the construct. Based on their feedback, the instrument was refined to accurately reflect the intended measurement objectives, supporting its use as a valid tool in this study.

Cronbach's Alpha	Alpha Based on Standardized Items	Number of Items
0.876	0.890	14

Table 5.1: Reliability Statistics

5.3.2 Descriptive Statistics

The main results of the analysis describe the statistics of three variables: usability, perception, satisfaction, and engagement on a sample size of seven participants. The Likert scale agreement was employed to show the response of the participants where 1 reflects strongly disagreeing and 5 strongly agrees.

The results of the usability factor for participants are shown in Table 5.2. At the end of each user test, participants responded to 9 questions about their experience using the VR environment. Overall, the usability evaluation of the VR for learning 3D transformations revealed positive feedback across most questions. Participants found performing transformations on virtual objects easy. The average rating for determining the direction of rotation (clockwise or counterclockwise) was 4.00 (SD = 1.15), with the standard deviation indicating some variability, suggesting not all users found it equally intuitive. The time taken for transformations was considered quick enough (M = 4.14, SD = 0.90). Users agreed that both the coordinate system and object sizes were appropriate (M = 4.57, SD = 0.53), and changing objects was straightforward (M = 4.57, SD = 0.53). Reading OpenGL commands (M = 4.43, SD = 1.13) and navigating between transformations (M = 4.43, SD = 1.13) were generally easy, although the variability in responses suggests some participants may have encountered challenges. Navigation within the VR environment received the lowest rating (M = 3.57, SD = 1.28), highlighting areas for improvement. These results emphasize the strengths of the VR environment while identifying usability challenges that need to be addressed in future developments.

Table 5.3 assesses participants' perceptions of virtual objects in the environment. Participants rated the ease of perceiving the position of virtual objects in 3D highly (M = 4.57, SD = 0.53), indicating strong agreement on the effectiveness of spatial representation. The orientation of virtual objects also scored well (M = 4.43, SD = 0.53), indicating ease for most users. Perceiving the movement of virtual objects scored slightly lower (M = 4.14, SD = 1.07), with a higher standard deviation suggesting that some participants found this more challenging. Overall, the findings show a positive perception of 3D objects in the VR environment, with room for improvement in movement perception.

In Table 5.4, participants expressed a moderate level of satisfaction and engagement with the VR learning experience. The mean satisfaction score regarding the overall VR learning experience for understanding 3D transformations was 4.00 (SD = 1.15), indicating a general sense of contentment, though the higher standard deviation suggests varied opinions among participants. Participants rated their engagement in the VR environment similarly, with a mean score of 4.00 (SD = 0.58), reflecting effective engagement in learning 3D transformations. Overall, while participants reported satisfactory levels of satisfaction and engagement, the variability in satisfaction suggests areas for enhancement in the VR experience.

Usability	**Mean**	**SD**
1. It is easy to transform (translation, rotation, scaling) to the virtual object using the VR controllers.	4.29	0.49
2. It is easy to determine clockwise and counterclockwise rotation.	4.00	1.15
3. The time taken to specify particular transformations is quick enough.	4.14	0.90
4. I think the number of units of the coordinate system is appropriate.	4.57	0.53
5. I think the size of the virtual objects is appropriate.	4.57	0.53
6. It is easy to change objects.	4.57	0.53
7. It is easy to read OpenGL commands.	4.43	1.13
8. It is easy to navigate between different transformations.	4.43	1.13
9. It is easy to navigate within the VR environment.	3.57	1.28

Table 5.2: Mean and standard deviation responses on the usability

Perception	**Mean**	**SD**
1. I think it is easy to perceive the position of the 3D virtual object in the VR environment.	4.57	0.53
2. I think it is easy to perceive the orientation of the 3D virtual object in the environment.	4.43	0.53
3. I think it is easy to perceive the movement of the 3D virtual object in the environment.	4.14	1.07

Table 5.3: Mean and standard deviation on the perception

5.3.3 Qualitative Analysis

The qualitative data collected from the open-ended questions and provided valuable insights into participants' experiences with the VR learning environment for 3D transformations. Responses through thematic analysis identified several areas in the VR

Satisfaction and Engagement	**Mean**	**SD**
1. I am satisfied with the overall VR learning experience for understanding 3D transformations.	4.00	1.15
2. I am engaged effectively in the VR environment for learning 3D transformations.	4.00	0.58

Table 5.4: Mean and standard deviation on the satisfaction and engagement

environment; hence, usability challenges, engagement factors, and potential environmental improvements are grouped into key themes here based on the question asked.

Difficulties with Virtual Environment Usability

The participants identified a number of elements within the VR environment that tended to create issues regarding usability. These themes include issues in rotation controls, interface design, and navigation. Rotation, in particular, was hard to perceive. One participant noted, "Rotation is a little hard to understand that the object is going clockwise or counterclockwise.". Moreover, there is frustration with specific features, such as navigation within the environment, with one user stating "Movement is not very natural.". Another frequently mentioned issue related to the control panel's size. A recurring concern was that the control panel was too large, blocking their view during interactions with the 3D transformations.

Factors Influencing Engagement

The aspects of the VR learning experience that contributed most to engagement varied among participants. Visual and interactive feedback was one factor; several responses mentioned animation effects as a critical engaging element. Participants remarked, "Animation effects with the object transforming are interesting and attracting me." and "Visualising the 3D transformations is very engaging.". Intuitive visuals and natural interactions were additional positive aspects of the VR experience. One user commented, "It gives me a more intuitive visual of the learning.".In addition, natural interaction with the user interface (UI) contributed positively to engagement, as expressed by another user, "The speed of receiving the feedback of transformation and the natural interaction with the UI." especially regarding objects transforming and the quick response of animations " I like the animation with the object transforming, it is interesting and respond quickly.". However, one user indicated that certain elements detracted from their engagement. The user pointed out the lack of precision in the scaling function, specifically noting the absence of precise controls for scaling objects. The user stated, "Missing decimal for scaling down the object, e.g., 0.5 scales as that's important and not straightforward to some people."

Suggestions for Enhancements

In the questions regarding suggestions that could be made to increase the usability of the VR environment, participants respondents suggested several features that could be added to this VR learning experience. Most pointed out the need to adjust the control panel, specifically to resize it. Others included better navigation options, like "option to fly around and walk faster." and a single-button press to show/hide the menu without needing to aim. Participants suggested a set of interactive features enabling them to interact with virtual objects for direct manipulative interaction with learning content. Some suggested adding sound effects to the animation: " I'd like to have some interaction with virtual objects." other suggestions included allowing trace visualization when an object is in motion. One participant said, "Maybe show the trace displaying how the object moves from one position to another.".

5.4 Discussion

The results of the analysis show how users perceive the immersive VR environment to learn 3D transformations. From descriptive statistics and qualitative data, it can also be determined that the users had quite good perceptions of the environment, as indicated by their responses and the mean scores for usability, satisfaction, and engagement. These results show that users generally found the VR setting engaging, intuitive, and effective in learning about transformations, but it also points out areas that need to be improved.

Although most gave very positive feedback, some issues regarding navigation and rotation controls remained critical challenges and needed improvement. Such variability in the users' experiences points to difficulties in certain aspects, most especially with specific areas like navigation, which received the lowest ratings. This shows that it is quite urgent that there be an improvement regarding navigation in further development. Improving rotation control and navigation mechanics would result in a more consistent user experience and thus a higher overall usability. With respect to perception, spatial representation and orientation of virtual objects were well-received by the participants. However, object movement seemed to be problematic for some users, indicating that whereas static information may be well-conveyed by the environment, improvement with respect to dynamic aspects is needed. The overall satisfaction and engagement levels were just average, with both showing a generally positive experience, while their variability does suggest further optimization of some features could be beneficial. The qualitative comments highlight how much the visual and interactive elements have helped sustain engagement. This agrees with other findings that have identified sophisticated visual feedback as integral to immersive learning VR applications [77]. It also points to the leading themes of most engagement in VR, such as visual animation and natural interactions, which again echoes prior research on interactivity for better learning outcomes in a virtual environment [65]. However, usability issues detracted from the overall experience and showed that improving these features would go a long way toward substantially enhancing user satisfaction. Participants' suggestions for features would go a long way in making the environment friendlier, interactive, and user-friendly, including resizing the control panel, adding navigation alternatives like flying, faster options for moving, and many other features reducing frustrations during user-environment interactions. Adding sound effects and tracing visualization for object movement may also enhance immersion, stimulating interactive learning. These recommendations also align with educational theories that favor interactive learning experiences for better engagement and retention [81].

5.5 Conclusions

The pilot study revealed that the immersive VR setting was generally well-received, with positive user experiences reported in terms of usability, engagement, and perception of 3D transformations. The participants liked the visuals and interactive features, which supported spatial understanding and learning. Problems were noted, however, in navigation and rotation controls, suggesting the need for better movement mechanics and interface adjustments. Perception of object movement also had to be enhanced despite positive feedback on static spatial representation. Participants suggested improvements such as resizing of user interface elements, different navigation schemes, sound effects, and motion trails to increase interaction and immersion. These findings informed system enhancement and validated the VR environment for progression to the main study in the multiphase mixed methods design.

Chapter 6

Main study

6.1 Introductions

The second phase of the research was developed based on the findings and user feedback from the pilot study. The insights obtained informed a series of improvements to the VR learning environment, enhancing its usability, interactivity, and instructional effectiveness. These refinements addressed key issues identified in the pilot phase, including navigation difficulties, rotation control challenges, and a lack of clarity in interface components.

With the improved version of the immersive environment in place, this phase aimed to evaluate how effectively the VR system supported students' learning of 3D transformations and their improvement in spatial visualization skills. A mixed-methods study was conducted to assess the impact of these enhancements on learning experience, spatial ability, and learning outcomes.

The following sections provide a comprehensive overview of the second phase of this research. This includes detailed descriptions of the improvements made to the immersive VR learning environment, the research methodology, participant characteristics, and the instruments used for data collection. Additionally, the chapter presents the experimental procedures, followed by the analysis and interpretation of both quantitative and qualitative results. The chapter concludes with a discussion of the findings, final conclusions, and suggestions for future work.

6.2 Improvements to the Environment

The findings from the pilot study highlighted several areas where the VR environment required refinement to improve learners' experience and effectiveness. Users reported challenges such as interface visibility, understanding transformation directions and movement mechanics. In response, a series of improvements were implemented in the environment to enhance the overall user experience.

Compared to the pilot version, the final version provided a clearer and more structured training experience. In the pilot study, some interface elements and transformation directions were less explicit, which occasionally confused. The refined version introduced clearer rotation indicators, improved navigation, trace visualization, and enhanced interface clarity, enabling learners to more systematically explore and understand transformation functions during the training session.

One of the first modifications involved scaling down the control panel to a more manageable size (see Figure 6.1). This change aimed to improve visibility and reduce screen obstruction during interaction, thereby allowing users to maintain a clearer view of the objects and scene. To support users in correctly interpreting rotational transformations, especially when viewed from different angles, I added the words ”clockwise” and ”counter-clockwise” directly to the control panel to indicate the direction of rotation. Additionally, within the scene, clear visual cues were implemented, which consist of animated circular arrows that visually represent rotational movement, thereby enhancing

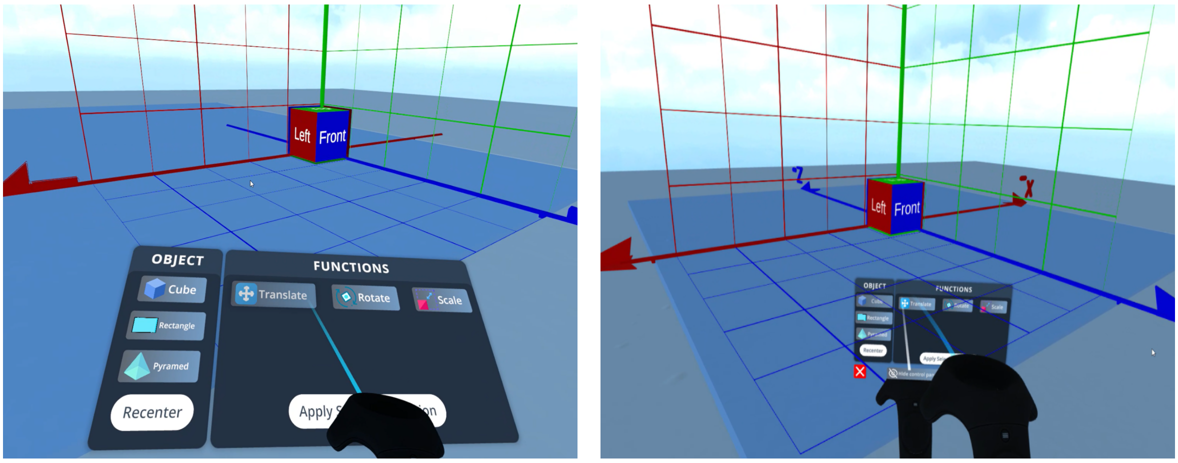
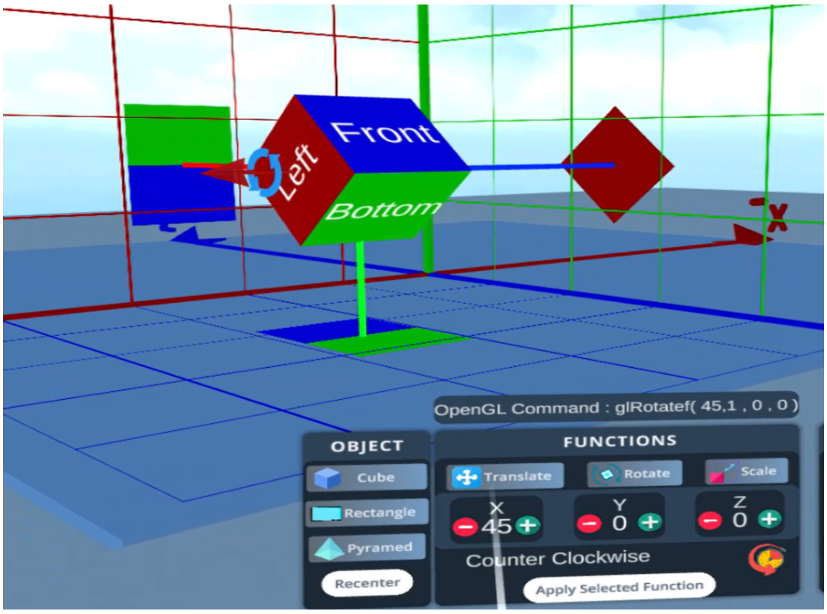


Figure 6.1: Control panel size before and after scaling



OpenGL Command : glRotatef(45,1 , 0 , 0)

Figure 6.2: Counter-clockwise rotation

users' ability to discern whether the object is rotating clockwise or counterclockwise (see Figure 6.2). These indicators significantly improved the user experience by providing a clear understanding, ensuring that users can accurately interpret the direction of rotation during their interactions with the scene. Furthermore, the interface provides users with a sequence of transformations, as illustrated in Figure 6.2, where the object is first translated and then rotated.

In addition, adjustments were made to the navigation to make it feel more fluid and natural. These changes included refinements to walking and the addition of flying around, contributing to smoother navigation and more intuitive spatial interactions within the immersive environment (see Figure 6.3). The introduction of a trace feature, which provides users with a visual path showing how an object moves or scales over time. This trace helped learners visualize the transformation effect before the manipulation process, offering greater insight into spatial understanding and aiding in the prediction of outcomes (see Figures 6.4 and 6.5).

Another enhancement was the addition of decimal input support for scaling transformations. This feature enabled users to apply more precise values when resizing objects, particularly in scenarios where fine-tuned adjustments were required. Additionally, visual rendering was refined by improving lighting and shadow effects, which

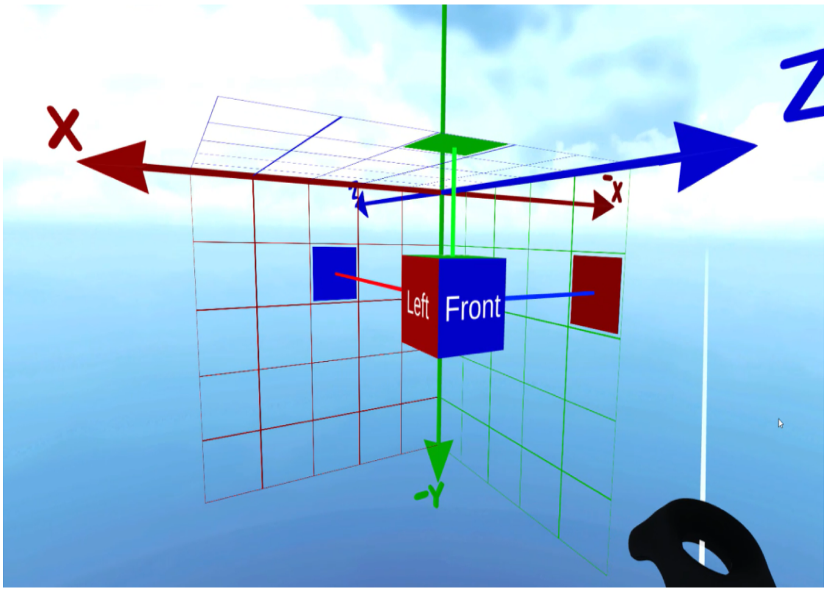


Figure 6.3: Flying downward along the negative Y-axis

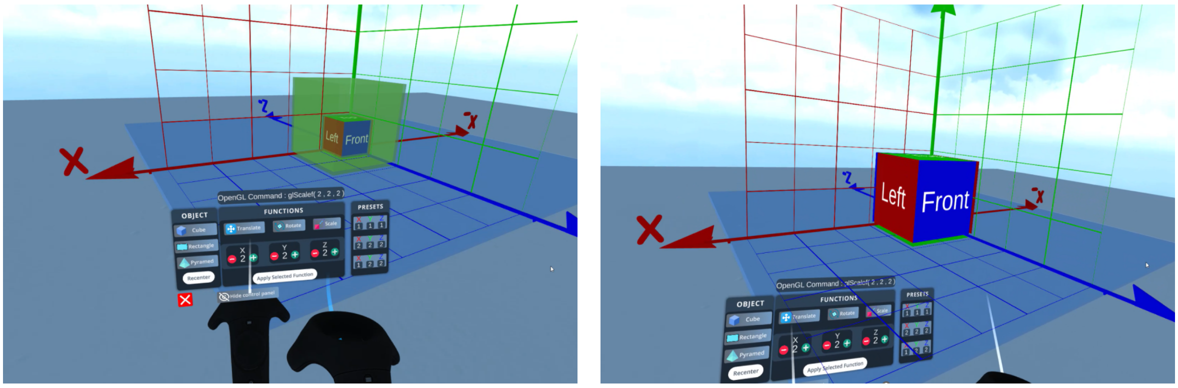


Figure 6.4: Tracing of scaling value(2, 2, 2)

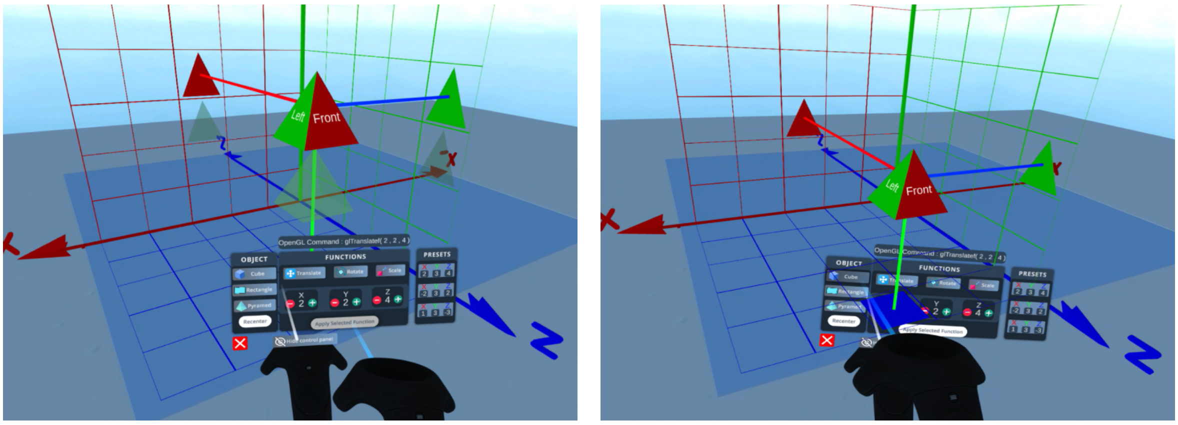


Figure 6.5: Tracing of translation value (2, 2, 4)

aimed to enhance depth perception and increase the clarity of object transformations.

Finally, to enhance interface usability and reduce cognitive load, a new interaction feature was implemented that allows users to show or hide the control panel with a single button press. This eliminates the need for precise aiming at the menu and supports cognitive processing by enabling easier access to the OpenGL commands.

6.3 Methodology

This study employed a mixed-methods research design, incorporating both quantitative and qualitative techniques to gain a comprehensive understanding of the effectiveness of the VR-based learning environment. The mixed methods approach enabled data triangulation, thereby improving the validity and richness of findings by combining numerical measurements with contextually based insights from participants [29].

To evaluate the impact of the immersive VR environment on students' spatial abilities and conceptual understanding of 3D transformations, a pre-experimental, one-group pretest–posttest design was implemented. This design enabled the comparison of students' performance before and after engaging with the VR system, offering a practical approach to measure learning gains.

It is important to note that this phase of the study did not include a comparison with an alternative teaching method. The primary objective of the main study was to explore the effectiveness of the immersive VR intervention in supporting students' understanding of 3D transformations and enhancing spatial visualization skills, rather than to conduct a comparative evaluation of instructional approaches. Given the exploratory focus of this phase, a one-group pretest–posttest design was considered appropriate for evaluating learning gains within the VR environment.

The quantitative component of the study consisted of two main assessments. First, the participants' spatial visualization skills were measured using the *Purdue Spatial Visualization Test: Rotations (Revised PSVT: R)* [43, 158], which was administered both before and after the VR intervention. Second, a 3D transformation knowledge test evaluated the learners' ability to comprehend and interpret transformations presented through both visual representations and OpenGL code.

The qualitative component consisted of a post-experience survey, which included open-ended questions that allowed participants to reflect on their learning experiences, the usability of the VR system, and the overall effectiveness of the immersive approach.

Statistical analysis relied on robust and widely accepted methods. Spearman's rank-order correlation [130], the spatial ability *Revised PSVT: R* [158], ANOVA [35], and Tukey's HSD test [148]. All statistical calculations were performed using R [109] and Python, using packages such as SciPy [151] and Pandas [84].

6.3.1 Participants

A total of 49 participants (32 male, 17 female) were recruited to participate in the main study. The sample consisted of 43 undergraduate and six postgraduate students from various academic backgrounds within the School of Computer Science at Trinity College Dublin. Specifically, 23 participants were enrolled in Computer Science, 13 in Engineering, and 13 represented other related disciplines. Participants were also asked to self-report their level of experience with virtual reality technology. Responses indicated a diverse range of VR familiarity, including one expert-level user, one advanced user, 14 intermediate users, 25 participants with limited experience, and 8 participants with no prior exposure to VR environments. In terms of age demographics, the majority of participants (46 out of 49) were between the ages of 18 and 24, while the remaining three participants were between 25 and 34 years old.

6.3.2 Data Collection Instruments

The study used multiple instruments to gather both quantitative and qualitative data.

Revised Purdue Spatial Visualization Test: Visualization of Rotations

The Revised Purdue Spatial Visualization Test: Visualization of Rotations (Revised PSVT:R), developed by Yoon [158], is an updated version of the original PSVT:R, designed by Guay [43]. This test is used to measure an individual's ability for 3-D mental rotational spatial visualization, which is a standardized test measure [158]. The test begins with two practice items and includes 30 questions about 3D objects that are depicted in 2D isometric format. The learner must next select the rotation that closely resembles the example provided from a list of five other objects and rotations (see Figure 6.6).

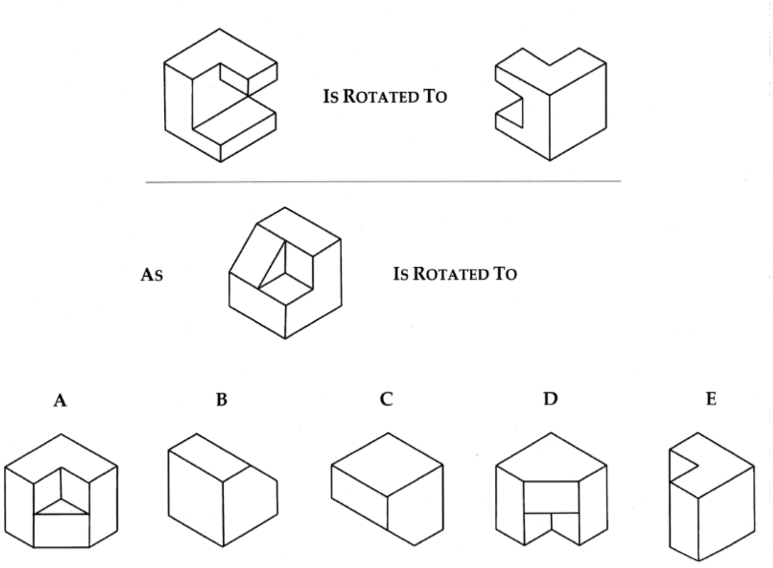


Figure 6.6: An example from (Revised PSVT: R) test [158]

Knowledge Test

The knowledge test to evaluate students' conceptual understanding of 3D transformations. This test measured their ability to interpret and apply transformation concepts effectively. The test included the following questions:

1. **Clockwise Rotation:** Which of the following OpenGL commands creates a rotation matrix, which performs a rotation by 45 in clockwise direction around the X-axis?

2. **Anti-clockwise Rotation:** Write an OpenGL command to rotate an object by 90 degrees anti-clockwise around the Z-axis.

3. **Scale:** Which OpenGL commands are used to execute that visual representation?

4. **Translation:** Which OpenGL commands execute that visual representation?

Post-experience Survey

The survey gathered student feedback regarding their experience with the VR learning environment. Participants were asked to reflect on various aspects of their interaction with the system, including engagement, learning challenges, and the perceived usefulness of real-time visualization and the integration of OpenGL commands. The questions were as follows:

1. How do you find the immersive VR environment for improving learning of 3D transformations?
2. What elements of the virtual reality learning process most influenced the extent of engagement—or lack thereof?
3. Overall, how satisfied are you with the immersive VR environment for learning 3D transformations and enhancing spatial visualization skills? (1 = "Very Satisfied"; 5 = "Very Dissatisfied")

6.3.3 Experiment Procedure

The study was conducted in a controlled laboratory setting and followed a structured sequence involving a single-session intervention. Each participant experienced the complete experimental procedure individually to ensure consistency in exposure and minimize environmental distractions.

1. **Pre-Intervention Assessment:** Participants began by completing a demographic questionnaire that gathered data on their academic background, VR experience, and age. Following this, they completed the Revised PSVT: R to establish a baseline measure of their spatial visualization ability.
2. **VR Learning Intervention:** Participants were introduced to the virtual environment through a brief tutorial session explaining the functionality of the VR

controllers and user interface. During the tutorial, participants were instructed on how to move within the virtual environment by walking physically within the tracked space and by using the controller to move forward, backward, and sideways. They were also shown how to "fly" within the environment to observe objects from different heights and viewpoints, and how to select transformation functions from the control panel and apply them to objects using the controller buttons. Before beginning the tasks, participants received standardized verbal instructions explaining that the session aimed to support their understanding of 3D transformations and the relationship between visual object manipulation and the corresponding OpenGL commands displayed in the interface. They were then allowed to explore the immersive environment freely to become familiar with its layout and interaction design. Following this familiarization phase, participants completed structured transformation tasks. They were required to apply translation and scaling operations and perform rotations around selected axes in clockwise or counter-clockwise directions, while observing how changing the order of transformations affected the final visual outcome. The system provided real-time visual feedback throughout the session. Each session lasted approximately 10–15 minutes, during which participants could repeat tasks and explore the environment from multiple perspectives without additional instructional guidance.

3. **Post-Intervention Assessment:** After completing the VR intervention, participants took the PSVT: R again to measure any improvement in spatial visualization ability. They also completed a knowledge test focused on assessing their understanding of 3D transformations in both visual and OpenGL code representations. Finally, participants responded to a post-experience survey that captured their perceptions of usability, engagement, and the educational effectiveness of the immersive VR environment.

Single Session Intervention

The effectiveness of a single-session intervention compared to continuous training in achieving long-term learning outcomes depends on several factors, including the instructional design, the complexity of the targeted skill, and individual learner differences. Short-term, one-time sessions may produce immediate improvements in specific abilities. Previous research has reported positive outcomes from single-session interventions aimed at developing spatial skills. Gómez-Tone et al. examined the impact of brief training sessions in immersive virtual reality on spatial skill development and reported improvements across multiple dimensions of spatial ability [41].Similarly, Suselo et al. employed an augmented reality tool to support students' understanding of 3D computer graphics transformations; following a single 15-minute session, students demonstrated enhanced comprehension of spatially demanding concepts [137]. Molina-Carmona et al. also found that a one-time 40-minute training session in a virtual environment led to improvements in participants' spatial perception skills [93]. In a related experimental study conducted within engineering education, different virtual reality systems were implemented and compared with a traditional non-VR approach in a single-session design with optional repetition. The findings demonstrated a significant improvement in student performance when VR was used [3]. In the present study, the intervention was conducted in an immersive virtual environment and lasted approximately 10–15 minutes. It aimed to support students' understanding of 3D transformations while enhancing spatial visualization skills and addressing the previously identified challenges.

Free Navigation

The review has demonstrated one challenge of using immersive VR as a tool in education: the user's learning experience may be hindered by the novelty of immersive virtual reality technology due to a lack of familiarity with VR [44]. If a person had never used immersive virtual reality technology or was unfamiliar with it, using a VR headset could initially feel unfamiliar and uncomfortable. Free navigation in immersive VR interventions allows users to gradually adapt to the experience and become more comfortable wearing the headset for extended periods. It allows users to gradually acclimate to the virtual setting, encouraging exploration and reducing the cognitive load associated with learning both the content and the interface simultaneously. The study supported free navigation, allowing users to explore the space naturally and interact with objects from multiple viewpoints. Participants could physically walk around the space using room-scale VR tracking and also had the option to use the VR controllers to "fly" or walk to different locations. By enabling users to observe objects from various perspectives, the free navigation capability reinforced key principles of egocentric encoding and active spatial learning, both of which are supported by cognitive and multimedia learning theories.

6.4 Results

6.4.1 Quantitative Outcomes

The pre-test and post-test descriptive statistics are shown in Table 6.1. Overall, spatial ability improved after the VR intervention, as evidenced by the mean post-test score being higher than the pre-test score.

Test	**Mean**	**SD**	**95% CI**
Pre-test	22.78	4.84	[21.39, 24.16]
Post-test	27.41	2.86	[26.59, 28.23]
Improvement	4.63	3.07	[3.75, 5.52]

Table 6.1: Descriptive statistics for pre-test, post-test ability scores and improvements, with 95% confidence intervals.

Figure 6.7 presents a boxplot comparison of pre-test and post-test scores, highlighting the distribution of participants' spatial ability before and after the VR learning activity.

To investigate the influence of baseline spatial ability on improvement from the VR

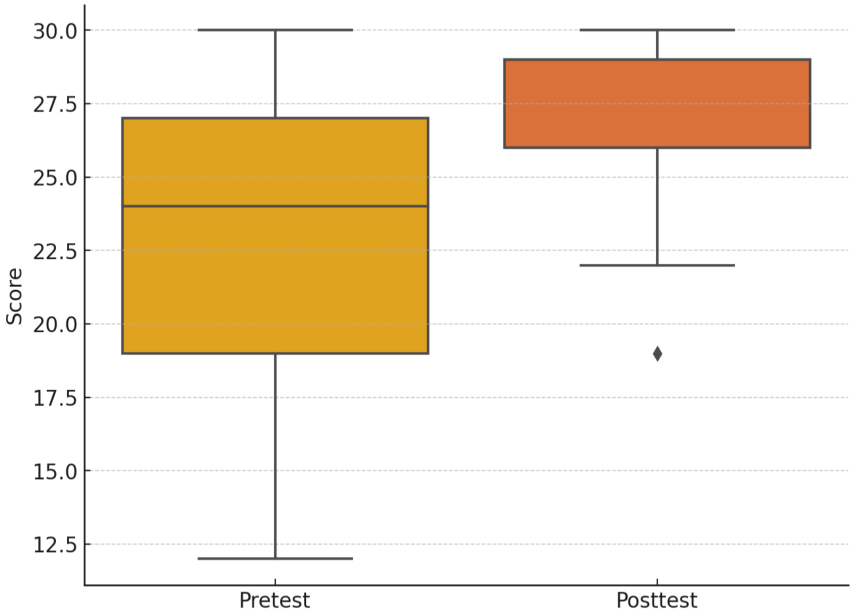


Figure 6.7: Boxplot of overall pre-test and post-test scores.

intervention, a comparison of pre-test mean and improvement scores was conducted across three performance groups (Figure 6.8). Participants were classified based on their initial spatial ability mean into: **Group 1**: (low performers, n = 15), **Group 2**: (medium performers, n = 17), and **Group 3**: (high performers, n = 17). The analysis revealed that participants in Group 1, who began with the lowest spatial ability, demonstrated the greatest improvement following the VR intervention. This suggests that individuals with initially lower spatial abilities may derive greater benefit from immersive VR-based learning environments compared to those who begin with higher spatial skills.

To evaluate the effect of the *VR-based learning intervention* on *students' spatial ability*, a **paired-samples t-test** was conducted comparing pre-test and post-test scores. The analysis revealed a **statistically significant improvement** in spatial ability following the VR experience. Participants' scores increased from a **pre-test mean** of ($M = 22.78, SD = 4.84$) to a **post-test mean** of ($M = 27.41, SD = 2.86$), yielding $t(48) = -10.55, p < .001$, two-tailed. The **average gain** in scores was **4.63 points**, with a **95% confidence interval** ranging from **3.75 to 5.52**. The effect size, calculated using **eta squared** ($\eta^2 = 0.70$) , indicates a **large practical impact**, confirming the substantial role that the immersive VR environment played in developing spatial

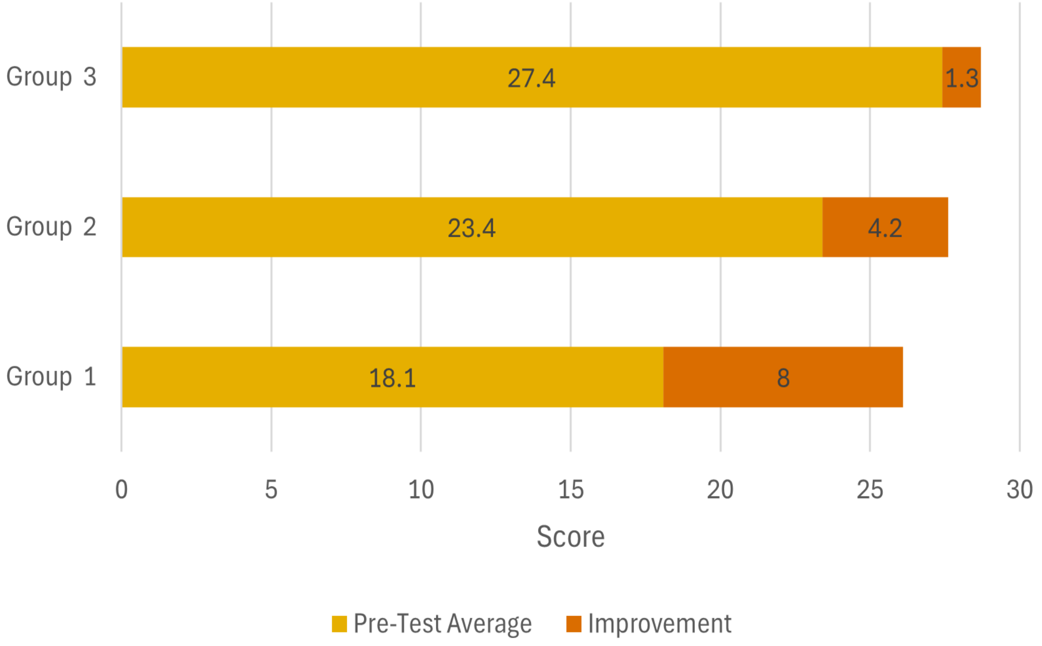


Figure 6.8: Pre-test averages and improvement scores by group.

reasoning skills.

The **knowledge test** results indicated varying levels of *conceptual understanding of 3D transformations* among the **49 participants**. Performance differed across the four questions: **26 students (53.1%)** correctly answered the clockwise rotation question, **29 students (59.2%)** correctly answered the anti-clockwise rotation question, **41 students (83.7%)** correctly answered the scaling question, and **30 students (61.2%)** correctly answered the translation question. Overall, the findings suggest a **moderate level of conceptual understanding**, with higher performance observed on scaling tasks compared to rotation-based questions.

Spearman's rank-order correlation was used to examine the relationship between *spatial ability improvement* and *conceptual understanding of 3D transformations*. Assumptions of linearity and homoscedasticity were tested prior to analysis. Results revealed a **significant but weak negative correlation** between the two variables $\rho = -0.31$, $n = 49$, $p = .033$, suggesting that participants who demonstrated *greater gains in spatial ability tended to score slightly lower on the conceptual knowledge test.* This unexpected finding suggests a possible disconnect between spatial skill gains and conceptual understanding of transformation logic and code.

Several factors might explain this outcome. One possibility is *cognitive overload*, where students may have focused more intensely on spatial manipulation tasks, thereby allocating less cognitive effort toward encoding conceptual information. Another possible explanation involves incongruence between *assessment formats* – the dynamic, real-time nature of the VR experience may not have translated well to the static format of the knowledge test.

A **one-way between-groups ANOVA (Analysis of Variance)** was also conducted to investigate whether *prior experience with VR* influenced the degree of *improvement in spatial ability*. Participants were grouped into three categories based on self-reported VR familiarity: **Group 1**: No experience (n = 8); **Group 2**: Limited experience (n = 25); and **Group 3**: Intermediate experience (n = 14). Due to incomplete responses, two participants were excluded from the analysis,resulting in a final sample of 47. The ANOVA results showed **no statistically significant difference** among the three groups in spatial improvement, $F(2, 46) = 0.05, p = 0.95$. Although the **effect size** (η^2= 0.35) was moderate, **Tukey's HSD** post-hoc comparisons confirmed that there were **no significant pairwise differences** among the groups. Mean improvement scores were as follows: **Group 1** ($M = 5.00, SD = 3.63$), **Group 2** ($M = 4.64, SD = 3.17$) and **Group 3** ($M = 4.57, SD = 2.98$).

These findings suggest that the VR-based learning experience benefited students **similarly regardless of their prior exposure** to virtual reality technologies. This supports existing literature which indicates that immersive environments can be effective educational tools even for learners with little to no previous experience using VR systems.

6.4.2 Qualitative Outcomes

In addition to the quantitative gains in spatial ability, participants also shared qualitative insights regarding their experiences within the virtual learning environment. Thematic analysis of these responses identified three core themes that shaped their learning experience:

Improved Spatial Visualization

Many students indicated that the immersive VR environment significantly improved their ability to visualize 3D transformations, especially in terms of rotation and perspective changes. Compared to traditional 2D instructional methods, they found the virtual environment offered a more intuitive and accurate spatial representation of transformation concepts. Several students specifically noted the clarity and insight provided by the system, with one stating, ”Helpful. You can visualize 3D transformations easily.” while another shared, ”It seems to help me visualize transformations better.” Others reflected on the spatial benefits of immersion and effectiveness of the rotation feature, such as ”It can help me understand different shapes, how they change at different angles.” and ”The immersive VR environment helped me to further understand how 3D shapes rotate.”

Engagement and Interactivity

The opportunity to freely manipulate objects and observe real-time changes was consistently highlighted by participants as a major strength of the VR learning experience. Many students found the environment to be highly engaging and intuitive, with several noting that the hands-on exploration significantly enhanced their conceptual understanding of 3D transformations. One participant remarked that “moving around the scene to capture the view from all sides was the most engaging part,” while another emphasized that “the ability to move freely in all directions makes the activity much more engaging.” This sense of spatial freedom enabled learners to develop a more accurate mental model of how transformations affect objects in three-dimensional space. Additionally, the ease of use was frequently praised, with students describing the interface as “easy to use,” “very straightforward,” and “intuitive.” Another student noted that “the ability to move around objects and get different viewpoints of them while changing their shape, size, rotation, etc.” was particularly helpful in maintaining engagement and reinforcing the learning content.

Adjustment and Navigation Challenges

Some participants initially experienced difficulties adapting to the VR interface, particularly in mastering the movement and interaction controls. Some participants experienced initial difficulties adapting to the VR interface, particularly in mastering the movement and interaction controls. Several students reported that navigating within the environment was confusing or overwhelming during the early stages of use. One participant commented, "It is complicated to understand at first, but very realistic and takes a little time to get used to," others echoed similar challenges, with remarks such as "I found the controls hard to use," and "I was most frustrated by the difficulties with setting up the controllers." Despite these early struggles, many users noted that their comfort with the system improved over time as they became more familiar with the controls and interface through continued interaction.

Satisfaction with VR Environment

Participants were asked to evaluate their overall satisfaction with the immersive VR environment in terms of its effectiveness in enhancing spatial visualization skills for learning 3D transformations. A substantial majority (**81.6%**) indicated that they were either **"Very Satisfied"** or **"Satisfied"** with the VR environment, while (**14.3%**) reported a neutral. Only a small minority (**4.1%**) expressed dissatisfaction.

A detailed summary of the satisfaction ratings is presented in Table 6.2. To investigate the relationship between learner satisfaction and learning outcomes, we analyzed whether students who scored higher on the knowledge test also reported higher levels of satisfaction. The results showed no significant correlation between test performance and satisfaction, suggesting that students' appreciation of the VR environment was not solely dependent on their conceptual understanding. Even participants who encountered difficulties in the knowledge test perceived the VR experience as beneficial for visualizing and understanding transformation concepts.

Statistic	**Value**
Mean	4.12
Standard Deviation	0.81
Minimum	2.00
Maximum	5.00
25th Percentile (Q1)	4.00
Median (Q2)	4.00
75th Percentile (Q3)	5.00

Table 6.2: Descriptive statistics for satisfaction ratings.

6.5 Discussion

The results of the main study provide strong evidence that the immersive VR-based learning environment significantly enhanced students' spatial visualization ability. This improvement was reflected in the increase in post-test PSVT:R scores compared to pre-test scores, with a large effect size ($\eta^2 = 0.70$). These findings reinforce existing literature supporting the use of immersive learning technologies to foster spatial reasoning skills [24, 18]. The interactive nature of the VR environment—allowing learners to manipulate 3D objects and receive real-time visual feedback—appears to have played a pivotal role in this improvement, bridging the gap between their visual-spatial representation and abstract transformation concepts.

One of the most notable outcomes was the greater improvement observed among students who initially had lower spatial ability. This finding suggests that immersive VR may be particularly beneficial for learners who typically struggle with spatial reasoning, supporting prior research showing that such environments can help mitigate disparities in spatial skills [39]. The ability to physically engage with objects, view transformations from multiple perspectives, and explore visual feedback in real-time offers a form of embodied learning not afforded by traditional 2D instructional methods.

This benefit is especially relevant for students from underrepresented backgrounds, including those with limited access to spatial learning tools or prior VR experience. As highlighted in related research, learners from lower-income or minority communities often face systemic barriers in developing spatial cognition due to limited educational resources access[152]. Research has shown that these learners often face compounded challenges, including reduced access to quality educational materials and spatial learning opportunities [152]. For these groups, the embodied, experiential nature of VR may offer a more equitable and engaging alternative to traditional teaching approaches, helping to level the playing field in skill development. Future studies could investigate how long or frequent VR training sessions affect the development of spatial abilities, especially for students who begin with weaker spatial abilities.

Although improvements in spatial ability were encouraging, an unexpected finding emerged in the form of a weak negative correlation between spatial skill gains and performance on the 3D transformation knowledge test ($\rho = -0.31, p = .033$). This suggests that improvements in spatial visualization did not directly translate to better conceptual understanding of 3D transformation sequences or OpenGL coding. Cognitive overload could be one reason for this discrepancy, where students may have focused heavily on spatial tasks within the immersive environment, leaving fewer cognitive resources for abstract retention of concepts. Another reason for this outcome might have been the different formats of the assessments; the VR experience was very dynamic, whereas the knowledge test used static representations of changes.

Interestingly, the results did not show significant differences in spatial skill gains based on previous levels of VR experience ($F(2, 46) = 0.05, p = 0.95$). This finding indicates that the VR-based learning experience was effective regardless of participants' familiarity with VR technology, aligns previous studies showing that immersive virtual environments can support learning for individuals with little to no previous VR experience [114]. This has practical implications for broader educational adoption, as it suggests that VR learning modules can be implemented without extensive user training.

The qualitative data collected via the post-experience survey provided valuable insight into students' perceptions of the VR-based learning environment. Participants consistently reported that the system improved their understanding of spatial visualization, particularly for challenging concepts like rotation and perspective changes. Many described the experience as more intuitive, engaging, and effective than traditional learning methods. The ability to manipulate objects in real time and receive immediate feedback was cited as especially helpful in making abstract concepts more tangible. These findings align with previous work highlighting the role of interactivity and embodiment in supporting cognitive development through VR [98, 51].

However, a few students reported initial difficulty navigating the VR interface, indicating a need for improved onboarding and orientation. Some participants also experienced mild disorientation or control-related frustrations early in the session, though these issues typically resolved with continued use. These insights underscore the need for thoughtful instructional design when implementing VR in education, ensuring that learners receive adequate support to make the most of the technology.

Despite these minor challenges, overall satisfaction was high (**81.6%** of participants reported being "Very Satisfied" or "Satisfied" with the learning experience. Interestingly, there was no significant correlation between satisfaction levels and knowledge test performance, suggesting that even students who found the conceptual material challenging still perceived the VR tool as helpful for visual understanding. This further supports the view of VR as a cognitive aid—one that supports visualization and spatial reasoning, even if additional instructional support may be needed to reinforce abstract content.

In sum, the findings from this phase of the study confirm that immersive VR offers considerable promise for supporting spatial learning in computer graphics education. The positive effects on spatial ability, particularly for students with lower initial skills, as well as the high engagement and satisfaction ratings, suggest that immersive VR environments can complement traditional instructional strategies. However, future work should address the limitations observed—particularly the disconnect between spatial gains and conceptual knowledge—and explore longer interventions, adaptive scaffolding, and VR-integrated assessments to enhance both understanding and retention.

6.6 Conclusion

This study indicates the effectiveness of immersive virtual reality environments in enhancing spatial ability and supporting the learning of 3D transformations in computer graphics education. The findings suggest that interactive 3D environments, which allow real-time manipulation and feedback with transformations, offer significant benefits especially for students with initially lower spatial skills. VR enables learners to explore concepts from multiple perspectives, facilitating spatial understanding that traditional 2D instructional methods cannot provide. The observed large effect size in spatial ability improvements highlights the potential of VR as a powerful educational tool to address spatial reasoning challenges.

However, the relatively weak relationship between gains in spatial ability and scores on the conceptual knowledge test indicates that improved spatial skills do not automatically result in stronger conceptual understanding. This highlights the importance of incorporating instructional scaffolding into immersive learning experiences. Features such as guided learning paths, adaptive feedback, and post-VR reinforcement activities can help bridge the gap between enhanced visualization and deeper conceptual understanding.

Despite these difficulties, students' qualitative feedback was overwhelmingly positive. They reported high levels of engagement, interactivity, and improved comprehension of transformations within the VR environment. The high satisfaction ratings reflect the intuitive nature of the VR interface and its effectiveness in supporting visual-spatial learning. The lack of significant impact of prior VR experience on learning gains indicates that a variety of learners, regardless of their level of VR technological experience, can benefit from immersive learning settings.

Future studies should examine the long-term retention of spatial skills developed through VR, explore scalable deployment in various instructional contexts, and assess the impact of collaborative virtual environments that promote peer-supported learning. In addition, refining the assessment tools to better align with the interactive and dynamic nature of VR could improve the evaluation of conceptual learning within immersive systems. Overcoming these areas will be the key to advancing VR as a medium in education, one that bridges the gap between abstract theoretical concepts and applied spatial skills in computer graphics and beyond.

Chapter 7

Expert Survey

7.1 Introductions

Following the main study involving student participants, an expert evaluation was conducted to obtain informed feedback on the educational value, usability, and interactivity of the virtual immersive learning environment that was developed. While the student study provided valuable evidence on the impact of the VR system on spatial ability and conceptual understanding, expert input was necessary to triangulate the findings and strengthen the reliability and credibility of the conclusions from an educational perspective.

As the third phase of the multiphase mixed-methods design, the expert study builds directly on the students' findings and serves as an independent validation component within the overall research framework. It provides a professional evaluation of the pedagogical alignment, usability, and instructional coherence of the immersive VR intervention, thereby strengthening the methodological rigor and overall research contribution beyond student-based findings.

Experts in fields such as computing education and human-computer interaction (HCI) offer unique insights into the appropriateness and effectiveness of educational technologies. Their evaluation helps identify design strengths, usability considerations, and opportunities for refinement that may not be fully captured through the student study. The following sections describe the methodology, participant characteristics, data collection, and findings.

7.2 Methodology

This expert evaluation employed a mixed-methods approach to evaluate the immersive virtual learning environment from an expert perspective, integrating both quantitative and qualitative techniques to obtain a comprehensive understanding of its educational effectiveness, usability, and interactivity.

To assess the system's pedagogical and design effectiveness, a post-evaluation survey was distributed to a purposive sample of subject-matter experts from the School of Computer Science after they engaged with the VR environment. The survey included Likert-scale items covering key areas such as conceptual clarity, interface usability, interactivity, and the educational impact of the VR-based 3D transformation tasks. Additionally, the survey included an open-ended question that invited experts to provide further comments or suggestions for improving the immersive learning environment.

The quantitative data were analyzed using SPSS. Descriptive statistics were used to summarize patterns and central tendencies across evaluation dimensions. Instrument reliability was assessed using Cronbach's alpha to evaluate internal consistency. Face and content validity were ensured through iterative input from domain experts during the survey design process, while construct validity was assessed using factor analysis to confirm that the instrument accurately captured the intended constructs.

The qualitative component of the study was derived from an open-ended question included in the post-evaluation survey, which invited experts to provide reflective feedback on specific aspects of the VR learning environment, such as usability, interactivity, and educational effectiveness.

7.2.1 Participants

A total of sixteen experts participated in the evaluation of the immersive VR learning environment. The sample consisted of one Professor, two Associate Professors, five Assistant Professors, six Lecturers, and two Teaching Assistants. Their teaching experience ranged from less than one year to 29 years, representing both early-career educators and senior academics. Specifically, two participants had less than one year of experience, two had between 1 and 5 years, three had between 6 and 10 years, four had between 11 and 15 years, three had between 16 and 20 years, and two had more than 20 years of teaching experience.

The experts represented various sub-disciplines within computer science. Nine specialized in Computer Science, three in Artificial Intelligence, two in HCI and VR, one in Software Engineering, and one in Robotics and Programming. Most participants were affiliated with the Department of Computer Science at Princess Nourah bint Abdulrahman University and had experience teaching programming, graphics, and HCI-related courses.

7.3 Results

7.3.1 Quantitative Analysis

To assess the reliability and construct validity of the expert evaluation instrument, a series of statistical analyses was performed. These analyses aimed to ensure that the post-evaluation survey reliably captured expert perceptions regarding the educational effectiveness, usability, and interactivity of the VR learning environment.

Reliability Analysis

Cronbach's Alpha was calculated to assess the internal consistency of the ten items. The results, shown in Table 7.1, indicate a **high level of reliability** ($\alpha = 0.852$), which supports the reliability of the instrument used to evaluate the VR environment.

Cronbach's Alpha	Alpha Based on Standardized Items	Number of Items
0.852	0.865	10

Table 7.1: Reliability Statistics

Validity and Factor Analysis

The construct validity of the instrument was assessed using Exploratory Factor Analysis (EFA), specifically employing *Principal Axis Factoring* with *oblique rotation (Oblimin).* This method was selected because it allows for the correlation between factors—an appropriate choice given that constructs such as usability, interactivity, and perceived learning effectiveness are likely to be interrelated rather than entirely independent.

Before running EFA, the suitability of the data for factor analysis was assessed using the **Kaiser-Meyer-Olkin (KMO)** measure and **Bartlett's Test of Sphericity**. The KMO value was 0.737, which falls within the **middling to good** range, indicating that the sample was adequate for reliable factor extraction [54]. Additionally, Bartlett's Test of Sphericity was **statistically significant**, $\chi^2(45) = 63.96$, $p = .033$, suggesting that the correlation matrix was not an identity matrix. This result confirms that the variables are sufficiently correlated to proceed with factor analysis.

The analysis extracted **three factors** with eigenvalues greater than 1, explaining a cumulative variance of **63.66%**. This suggests that **three distinct dimensions** underlie the evaluation instrument, likely corresponding to perceived educational effectiveness, usability, and Interactive engagement features.

The **communalities** representing the amount of variance in each variable explained by the extracted factors ranged from **0.399 to 0.960**, with most values exceeding **0.50**, demonstrating that the *majority of the variance was captured effectively by the model.*

However, the factor solution required more than **25 iterations** to converge, suggesting a **complex item structure** with overlapping constructs. Despite this, the extracted **factor loadings** demonstrated meaningful item groupings, supporting the multidimensional nature of the evaluation instrument. For example, Items such as *"The VR interface is intuitive for basic transformations"* and *"for applying multiple transformations"* loaded strongly onto a **usability-related factor**. Items related to *spatial skill improvement* and *real-time visual feedback* were loaded on an **educational effectiveness factor**. In contrast, features such as *object manipulation* and *navigation* corresponded to an **interactivity-related factor**.

This provides strong support for the **construct validity** of the evaluation tool and demonstrates that the items successfully differentiate between various aspects of user experience in the VR environment.

Descriptive Statistics

Descriptive statistics were calculated to evaluate the overall perceptions of the expert participants regarding various dimensions of the VR learning environment. These included perceived interactivity and engagement, educational effectiveness and interface usability. Experts rated each item on a 5-point Likert scale, where 1 = strongly disagree and 5 = strongly agree.

The results indicate a generally **high level of agreement** across all dimensions, with mean scores ranging from **4.31 to 4.81**, suggesting that experts found the VR system to be both effective for learning and easy to use. These ratings highlight strong support for the immersive environment as a valuable educational tool.

As shown in Table 7.2, items related to educational effectiveness received notably **high ratings**. For instance, *"Using the VR environment improves students' spatial visualization skills"* and *"The VR system effectively supports students in understanding 3D transformation concepts"*, both received mean scores of **4.69**. The experts also appreciated the real-time responsiveness of the environment ($M = 4.31$), further confirming the support of the environment for conceptual understanding.

Educational Effectiveness	**Mean**	**SD**
1. The complexity of 3D transformations (e.g., translation, rotation, scaling) in the VR environment is appropriate for student learning.	4.56	0.512
2. The 3D transformations in the VR environment effectively support students in understanding these concepts.	4.69	0.479
3. Seeing real-time changes in the VR environment helps me understand OpenGL 3D transformations better.	4.31	0.793
4. Using the VR environment improves students' spatial visualization skills.	4.69	0.479

Table 7.2: Mean and standard deviation for Educational Effectiveness

The **highest overall mean** rating was given to the item *"The visual representation of 3D transformations is clear and easy to interpret"* ($M = 4.81, SD = 0.403$), underscoring the importance of visual clarity in supporting learning, as shown in Table 7.3. Other items in this dimension, such as *ease of applying basic and sequential transformations*, also received high scores ($M = 4.56$ and $M = 4.44$, respectively), highlighting the usability of the system.

Interface Usability	**Mean**	**SD**
1. The visual representation of 3D transformations in the VR environment is clear and easy to interpret.	4.81	0.403
2. The VR interface is intuitive for performing basic transformations, such as translation, rotation, and scaling.	4.56	0.512
3. The VR interface is intuitive for applying multiple transformations in sequence.	4.44	0.512

Table 7.3: Mean and standard deviation for Usability

In Table 7.4, the item *"The interactive elements in the VR environment (e.g., manipulable objects, real-time feedback) are helpful for learning 3D transformations"* received a **high mean** score of 4.75, reflecting positive perceptions of the system's hands-on features. Similarly, the item *"The interactive features of the VR environment keep students actively engaged during learning"* received a strong rating ($M = 4.50, SD = 0.816$), indicating that the system effectively supports learner engagement. The use of immersive mechanics such as *head movement and spatial navigation* was also positively received ($M = 4.31$), suggesting that these features enhance learners' perception of 3D space and contribute to maintaining attention and involvement during tasks.

These results, together with the factor and reliability analysis, indicate that the VR learning environment is perceived by experts as a pedagogically sound, visually clear, and highly interactive tool that is well-suited for enhancing students' understanding of 3D transformations and improving spatial visualization skills.

Interactivity and Engagement	Mean	SD
1. The interactive features of the VR environment (e.g., object manipulation, real-time feedback) keep students actively engaged during learning.	4.50	0.816
2. The use of head movement and navigation in VR enhances students' perception of 3D space.	4.31	0.479
3. The interactive elements in the VR environment (e.g., manipulable objects, real-time feedback) are helpful for learning 3D transformations.	4.75	0.447

Table 7.4: Mean and standard deviation for Interactivity and Engagement

7.3.2 Qualitative Analysis

To complement the quantitative findings, a qualitative analysis was conducted based on the open-ended responses collected from experts at the end of the post-evaluation survey. The analysis aimed to capture additional insights into expert perceptions of the VR learning environment. These responses were coded inductively and grouped into the following key themes:

Educational Potential and Future

Several experts praised the system's educational value and its potential for broader adoption. The comments highlighted how the VR environment supports conceptual understanding of 3D transformations and recommended its integration into university-level computer science curricula. For example, one expert stated, "I think this environment can help students to understand the concepts," while another remarked, "It is really fantastic for the future generation, and I would recommend bringing this as a course for Computer Science students at the college level.". These statements demonstrate a high level of confidence in the educational value of the environment and its potential for widespread adoption in formal learning environments.

Visual and Interaction Design Suggestions

Experts provided specific suggestions to improve the visual and interaction elements of the environment. These included calls for more realistic or diverse object representations and enhanced intuitiveness. For example, one expert noted the need to "improve the visualization of objects so that it includes not only geometrical shapes but also real-world ones," and another suggested, "make the menu easier and more intuitive." These suggestions reflect a desire for richer, more realistic visuals and improved accessibility of interface elements for novice students.

Interactivity and Control Precision

While the interactive components were generally appreciated, a few experts noted the need to refine the control mechanisms to improve precision and user orientation. An expert said, "I suggest adding a shadow-like effect on where the controller (cursor) is currently pointing at." Another recommended "Reduce the sensitivity of the controller." These suggestions underscore the importance of precise and responsive interaction, especially in immersive learning environments.

7.4 Discussion

Quantitative analysis showed consistently high ratings across all measured dimensions. Educational effectiveness was particularly well supported, with experts strongly agreeing that the VR system enhances understanding of transformations and improves spatial visualization skills. These findings are aligned with previous studies that highlight the role of spatial immersion and embodied interaction in promoting deeper cognitive engagement [11] and better conceptual retention [103].

The convergence between expert evaluations and the positive outcomes observed in the student study provides triangulated evidence supporting the validity and pedagogical soundness of the immersive VR framework.

A notable feature noted by participants was the interactive design of the system, which includes manipulable 3D objects and real-time feedback. The item "The interactive elements in the VR environment are helpful for learning 3D transformations" received one of the highest ratings ($M = 4.75$). This high score suggests that hands-on interaction with virtual content is not only engaging but also instrumental in supporting student learning, aligning with research showing that interactive learning environments encourage active engagement and exploration [122], and that VR provides learners with deeply immersive and highly engaging learning experiences [28].

The usability of the interface was also well received. The experts found the environment to be intuitive for applying transformations and the clear layout of the interface.

Qualitative responses reinforced these findings. Experts commented positively on the immersive potential of the system and recommended a broader application in computer science education. Suggestions for improvement included improving visual realism, making the UI more intuitive, and reducing controller sensitivity - practical insights that will guide future development.

7.5 Conclusion

The expert study provided a well-rounded assessment of the system's educational potential, usability, and interactive effectiveness. The findings indicate that the VR system was well-received across multiple dimensions. Experts rated it highly for its educational value—particularly in improving spatial visualization skills and supporting conceptual understanding of transformations. Interactive elements, such as real-time feedback and object manipulation, were seen to be particularly beneficial in promoting engagement and deepening learning. The usability of the interface, including navigation and controller responsiveness, was also positively evaluated, though some suggestions were made to improve intuitiveness and reduce sensitivity. These insights reinforce the importance of iterative, user-centered design in educational VR systems, particularly for learners unfamiliar with virtual environments. In general, the results confirm that the immersive virtual reality environment effectively supports student learning in spatial domains and aligns well with the expert expectations for educational technology. This feedback will guide further system development and inform future research and curriculum integration. The positive reception from domain experts also suggests strong potential for broader adoption of immersive technologies in STEM education, especially for teaching abstract spatial concepts that are traditionally challenging to grasp.

Chapter 8

Conclusion and Future Work

8.1 Conclusion

This research explored the design, implementation, and evaluation of an immersive virtual learning environment aimed at enhancing students' understanding of 3D transformations and improving spatial visualization skills. The study adopted a mixed-method multiphase approach consisting of a pilot study, a main intervention, and an expert evaluation to provide a comprehensive analysis of the immersive learning environment.

The pilot study established the technical feasibility of the VR prototype and gathered initial user feedback, revealing strong engagement and preliminary learning benefits. This phase informed key refinements of the system, particularly in the areas of interaction and interface clarity.

The main study, which involved pre- and post-testing, spatial ability assessments, and user perception surveys, demonstrated a statistically significant enhancement in spatial ability and supported the learning of 3D transformations within computer graphics education. Participants reported high levels of satisfaction and engagement, emphasizing the value of immersive VR as an effective medium for overcoming spatial reasoning difficulties in educational contexts.

The expert evaluation provided further validation from domain professionals, who consistently rated the system highly across dimensions such as educational effectiveness, interactivity, engagement, and usability. Notably, experts emphasized the benefits of real-time feedback, manipulable 3D objects, and immersive navigation for supporting conceptual learning. Constructive feedback was also offered regarding interface intuitiveness, object realism, and controller sensitivity, informing areas for further development.

Together, these phases confirm that the immersive VR system effectively supports learning and is positively received by both learners and experts. The findings underscore the value of integrating VR into computing and STEM education, especially for topics involving abstract spatial reasoning and 3D manipulation.

8.2 Future Work

While the studies provided valuable insights into the educational effectiveness and usability of the immersive VR system, several limitations also highlight opportunities for future development and research.

Limitations related to hardware setup and controller sensitivity affected the user experience. The reliance on the HTC Vive headset and its controllers occasionally caused navigation challenges, jitter, and difficulties in accurately selecting small interface elements. These issues sometimes drew focus away from the primary learning tasks. Future implementations could benefit from adopting more user-friendly, wireless VR headsets—such as the Meta Quest series—that offer improved stability, ease of setup, and better controller responsiveness. Additionally, enhancing the interface design to accommodate more precise and intuitive input methods could further reduce frustration and support smoother interactions.

The research focused on short-term learning outcomes, assessing students' understanding immediately after the intervention. Future studies should incorporate longitudinal designs to investigate long-term retention of spatial and conceptual knowledge, as well as its transfer to other contexts and problem-solving tasks.

There is also a need to refine assessment tools to reflect better the interactive, exploratory and real-time nature of VR-based learning. Current measurement approaches often focus on static evaluations, which may fail to capture the depth of conceptual understanding developed through immersive, hands-on experiences. Designing VR-integrated assessments could provide richer insights into learners' progress and comprehension, helping to position VR as a transformative educational medium that effectively connects abstract theoretical knowledge with applied spatial reasoning skills.

To fully evaluate the potential of curriculum integration, future work should explore structured implementation within formal educational programs, ideally through collaborative design with instructors. This could include guided lesson plans, assessment strategies, and scaffolding materials aligned with academic standards.

In summary, these limitations provide clear direction for future work that can enhance the system's educational impact, usability and scalability.

Appendices

Appendix A

Ethics

14/02/2024

Title: Pilot Study of Using Virtual Reality Environment Learning of 3D Transformations in Computer Graphics

REAMs No: 3029

Dear Maha Alobaid,

Your application has been reviewed by the relevant Research Ethics Committee (REC) and we are pleased to inform you that the above project has been approved.

Please note that any documents submitted for GDPR purposes in association with your ethics application are approved by the REC from an ethical perspective only (GDPR compliance is assumed, as per your uploaded letter of approval from the DPO).

It is the responsibility of the researcher/research team to ensure that, if applicable, all aspects of the study are executed in compliance with the General Data Protection Regulation (GDPR), the Health Research Regulations, Data Protection Act 2018, particularly regarding the storage and destruction of data arising from the research, and adhere to any relevant Health & Safety regulations.

Please note the reporting requirements outlined, in particular the need for:

- An immediate report of any serious or unexpected adverse event should be sent immediately to your REC via email. The Procedures for Reporting Adverse Events are outlined in the application. The Adverse Event form are available here.
- Any other unforeseen events should also be reported using this form and sent to your REC via email. The Adverse Event form are available here.
- An end of project report is due one year from the end of project date. The form is available here. This should be sent to your REC via email.
- If the data collection period is longer than 1 year, an annual report should be submitted. The form is available here. This should be sent to your REC via email.

You, and your research team (where applicable), are responsible for conducting the research strictly in the manner outlined in your application and supporting documentation, and in compliance with it. Proposed changes or amendments to the approved study must be submitted to the REC for approval in advance of any changes or amendments being implemented. In the event that the changes or amendments are significant, the REC may require a new submission. This ethical approval expires with the end dates of the project as stated in the application.

If you have any queries regarding this decision, please contact the Chair of your REC.

We wish you all the very best with your research project.

Kind Regards,

The REC

NB. If your study is to be conducted outside TCD, e.g. in a hospital site, please note that Trinity College REC approval does not of itself entitle you to conduct research in an external site. In this regard, the onus is upon you - the researcher, to ensure that all permissions have been obtained, and that any other requirements of the study site have been satisfied

NB. If your study involves a trial of medicinal products or medical devices, apps on humans you must provide a copy of your Clinical Trial Sponsorship from TCD - indicating that you have the appropriate trial insurance and sponsor oversight".

PARTICIPANT CONSENT FORM

Pilot Study of Using Virtual Reality Environment Learning of 3D Transformations in Computer Graphics

Lead Researchers: Maha Aobaid and Dr. Michael manzke

Aim of Study: The pilot study aims to explore the usability and user experience of utilizing virtual reality (VR) technology for learning 3D transformations in computer graphics.

Procedures of this Study: In this study, you will be asked to put on a VR headset and be immersed in a VR environment t to learn the basic 3D transformations in computer graphics. After that, you will be asked to fill out a questionnaire to evaluate the ease of navigation and interaction within the VR environment for learning and identify potential usability issues, challenges, or improvements needed in the VR environment.

Publication: The outcome of this research is expected to be published in a PhD thesis and an international conference or journal paper in the areas of computer graphics, virtual reality, and computer science.

Conflicts of Interest: There are no conflicts of interest regarding the research topic or with any of the participants.

Declaration:

- I am 18 years or older and I am competent to provide consent.
- I have read or had read to me a document providing information about this research and this consent form. I have had the opportunity to ask questions, and all of my questions have been answered to my satisfaction, and I understand the description of the research provided to me.
- I agree that my data can be used for scientific purposes, and I have no objection that my data is published in scientific publications and PhD thesis.
- I understand that if I make illicit activities known, these will be reported to the appropriate authorities.
- I understand that I may refuse to answer any question and withdraw at any time without penalty.
- I understand that if the research results have been published that can no longer be attributed to me, it will no longer be possible for me to withdraw.
- I freely and voluntarily agree to participate in this research study without prejudice to my legal and ethical rights.
- I understand that no personal details about me will be recorded.
- I understand that if I or anyone in my family has a history of epilepsy or severe motion sickness, I proceed at my own risk.
- I understand that participating in this VR experience for a short duration carries minimal risk, so I proceed at my own risk.

Participant's Name (printed):

Participant's Signature:

Statement of Investigator's Responsibility: I have explained the nature and purpose of this research study, the procedures to be undertaken, and any risks involved. I have offered to answer any questions and thoroughly answered such questions. I believe that the participant understands my explanation and has freely given informed consent.

Researcher Contact Details:
Maha Alobaid- alobaidm@tcd.ie
School of Computer Science and Statistics
Stack B, Graphics, Vision, and Visualisation Group

Researcher's Signature:

Date:

13/05/2024

Title: Effectiveness of Immersive Virtual Environment in Learning 3D Transformations in Computer Graphics and Impact on Spatial Skills

REAMs No: 2854

Dear Maha Alobaid,

Your application has been reviewed by the relevant Research Ethics Committee (REC) and we are pleased to inform you that the above project has been approved.

Please note that any documents submitted for GDPR purposes in association with your ethics application are approved by the REC from an ethical perspective only (GDPR compliance is assumed, as per your uploaded letter of approval from the DPO).

It is the responsibility of the researcher/research team to ensure that, if applicable, all aspects of the study are executed in compliance with the General Data Protection Regulation (GDPR), the Health Research Regulations, Data Protection Act 2018, particularly regarding the storage and destruction of data arising from the research, and adhere to any relevant Health & Safety regulations.

Please note the reporting requirements outlined, in particular the need for:

- An immediate report of any serious or unexpected adverse event should be sent immediately to your REC via email. The Procedures for Reporting Adverse Events are outlined in the application. The Adverse Event form are available here.
- Any other unforeseen events should also be reported using this form and sent to your REC via email. The Adverse Event form are available here.
- An end of project report is due one year from the end of project date. The form is available here. This should be sent to your REC via email.
- If the data collection period is longer than 1 year, an annual report should be submitted. The form is available here. This should be sent to your REC via email.

You, and your research team (where applicable), are responsible for conducting the research strictly in the manner outlined in your application and supporting documentation, and in compliance with it. Proposed changes or amendments to the approved study must be submitted to the REC for approval in advance of any changes or amendments being implemented. In the event that the changes or amendments are significant, the REC may require a new submission. This ethical approval expires with the end dates of the project as stated in the application.

If you have any queries regarding this decision, please contact the Chair of your REC.

We wish you all the very best with your research project.

Kind Regards,

The REC

NB. If your study is to be conducted outside TCD, e.g. in a hospital site, please note that Trinity College REC approval does not of itself entitle you to conduct research in an external site. In this regard, the onus is upon you - the researcher, to ensure that all permissions have been obtained, and that any other requirements of the study site have been satisfied

NB. If your study involves a trial of medicinal products or medical devices, apps on humans you must provide a copy of your Clinical Trial Sponsorship from TCD - indicating that you have the appropriate trial insurance and sponsor oversight".

PARTICIPANT CONSENT FORM

Effectiveness of Virtual Environment in Learning 3D Transformations in Computer Graphics and Impact on Spatial Skills

Lead Researchers: Maha Aobaid and Dr. Michael manzke

Aim of Study: The study aims to understand the impact of an immersive virtual environment on learning 3D transformations in computer graphics and to explore their effects on improving students' spatial skills.

Procedures of this Study: Participants will begin by completing a demographic questionnaire and pre-test (Revised PSVT: R). They will then don a VR headset and engage in a virtual environment designed to teach basic 3D transformations in computer graphics. Following this, participants will complete a post-test (Revised PSVT: R) and a knowledge assessment to measure improvements in spatial skills and understanding of 3D transformations in computer graphics.

Publication: The outcome of this research is expected to be published in a PhD thesis and an international conference or journal paper in the areas of computer graphics, virtual reality, and computer science.

Conflicts of Interest: There are no conflicts of interest regarding the research topic or with any of the participants.

Declaration:

- I am 18 years or older and I am competent to provide consent.
- I have read or had read to me a document providing information about this research and this consent form. I have had the opportunity to ask questions, and all of my questions have been answered to my satisfaction, and I understand the description of the research provided to me.
- I agree that my data can be used for scientific purposes, and I have no objection that my data is published in scientific publications and PhD thesis.
- I understand that if I make illicit activities known, these will be reported to the appropriate authorities.
- I understand that I may refuse to answer any question and withdraw at any time without penalty.
- I understand that if the research results have been published that can no longer be attributed to me, it will no longer be possible for me to withdraw.
- I freely and voluntarily agree to participate in this research study without prejudice to my legal and ethical rights.
- I understand that no personal details about me will be recorded.
- I understand that if I or anyone in my family has a history of epilepsy or severe motion sickness, I proceed at my own risk.
- I understand that participating in this VR experience for a short duration carries minimal risk, so I proceed at my own risk.

Participant's Name:

Participant's Signature:

Kingdom of Saudi Arabia
Ministry of Education
Princess Nourah bint
Abdulrahman University
(048)

Graduate Studies and Scientific
Research Vice- Rectorate

المملكة العربية السعودية
وزارة التعليم
جامعة الأميرة
نورة بنت عبدالرحمن
(٠٤٨)

وكالة الجامعة للدراسات العليا والبحث العلمي

IRB Registration Number with KACST, KSA: HAP-01-R-059
September 05, 2024

IRB Log Number: 24-0805
Project Title: Expert Survey to Evaluate Immersive Virtual Environment in 3D Learning Transformations in Computer Graphics
Category of Approval: EXEMPT

Dear Maha Alobaid

Thank you for submitting your proposal to the PNU Institutional Review Board. Your proposal was evaluated considering the national regulations that govern the protection of human subjects. The IRB has determined that your proposed project poses no more than minimal risk to the participants. Therefore, your proposal has been deemed ***EXEMPT*** from IRB review. Please note that this approval is from the research ethics perspective only. You will still need to get permission from the head of the department in PNU or an external institution to commence data collection.Please note that the research must be conducted according to the proposal submitted to the PNU IRB. If changes to the approved protocol occur, a revised protocol must be reviewed and approved by the IRB before implementation. For ***any*** proposed changes in your research protocol, please submit a Request for Modification form to the PNU IRB. Please be aware that changes to the research protocol may prevent the research from qualifying for exempt review and require submission of a new IRB application or other materials to the PNU IRB. In addition, if an unexpected situation or adverse event happens during your investigation, please notify the PNU IRB as soon as possible. If notified, we will ask for a complete explanation of the event and your response.

Please be advised that regulations require that you submit a progress report on your research every 6 months. Please refer to the protocol number denoted above in all communication or correspondence related to your application and this approval. You are also required to submit any manuscript resulting from this research for approval by IRB before submission to journals for publication.

The researcher is personally liable for plagiarism and any violations of intellectual property rights.

IRB is not responsible for accuracy of statements on religious and cultural affairs so researchers must consult competent authorities.

For statistical services you are advised to contact the Data Clinic at the Health Sciences Research Center (hsrc-DC@pnu.edu.sa) or the Scientific Research Center at the Deanship of Scientific Research (dsr-rsc@pnu.edu.sa) extension 30711.

We wish you well as you proceed with the study. Should you have additional questions or require clarification of the contents of this letter, please contact me.

You can apply for research funding at (DSR-RS@pnu.edu.sa).

Sincerely Yours,

Dr. Najla AlMasoud

جامعة الأميرة نورة بنت عبدالرحمن
مجلس المراجعة المؤسسي
Institutional Review
Board (IRB)

05 Sept 2024

Najla

Chairperson, Institutional Review Board (IRB)
Associate Professor of Chemistry Science, Chemistry Department, College of Science
Princess Nourah bint Abdulrahman University, Riyadh, KSA

Appendix B

Study Instruments and Materials

1. Pilot Study
2. Knowledge Test and Post-Experience Survey
3. Expert Survey

Pilot Study of Using Virtual Reality Environment for Learning 3D Transformation in Computer Graphics

Usability

It is easy to transform (translation, scaling, rotation) to the virtual object using the VR controllers.

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree

It is easy to determine clockwise and counter clockwise rotation.

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree

The time taken to specify particular transformations is quick enough.

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree

I think the number of units of the coordinate system is appropriate.

○ Strongly agree
○ Agree
○ Neutral
○ Disagree
○ Strongly disagree

I think the size of the virtual objects is appropriate.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It is easy to change objects.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It is easy to read OpenGL command.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It is easy to navigate between different transformations.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

It is easy to navigate within the VR environment.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

What is your recommended amount of time for students to use the environment comfortably for and why?

Which part of the environment is difficult to use (if any) and why?

Perception

I think it is easy to perceive the position of the virtual object in 3D in the VR environment.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

I think it is easy to perceive the orientation of the virtual object in 3D in the environment.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

I think it is easy to perceive the movement of the virtual object in 3D in the environment.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

Satisfaction and Engagement

I am satisfied with the overall VR learning experience for understanding 3D transformations.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

I am engaged effectively in the VR environment for learning 3D transformations.

- ○ Strongly agree
- ○ Agree
- ○ Neutral
- ○ Disagree
- ○ Strongly disagree

What aspects of the VR learning experience contributed most to your engagement or lack thereof?

Improvement Suggestions

What improvements would you suggest enhancing the usability of the VR environment for learning 3D transformations?

Are there any specific features or functionalities you would like to see added to the VR learning experience?

Knowledge Test and Post-experience Survey

* Which of the following OpenGL commands create a rotation matrix, which performs a rotation by 45 in clockwise direction around the X-axis?

○ glRotatef(-45, 1, 0, 0)

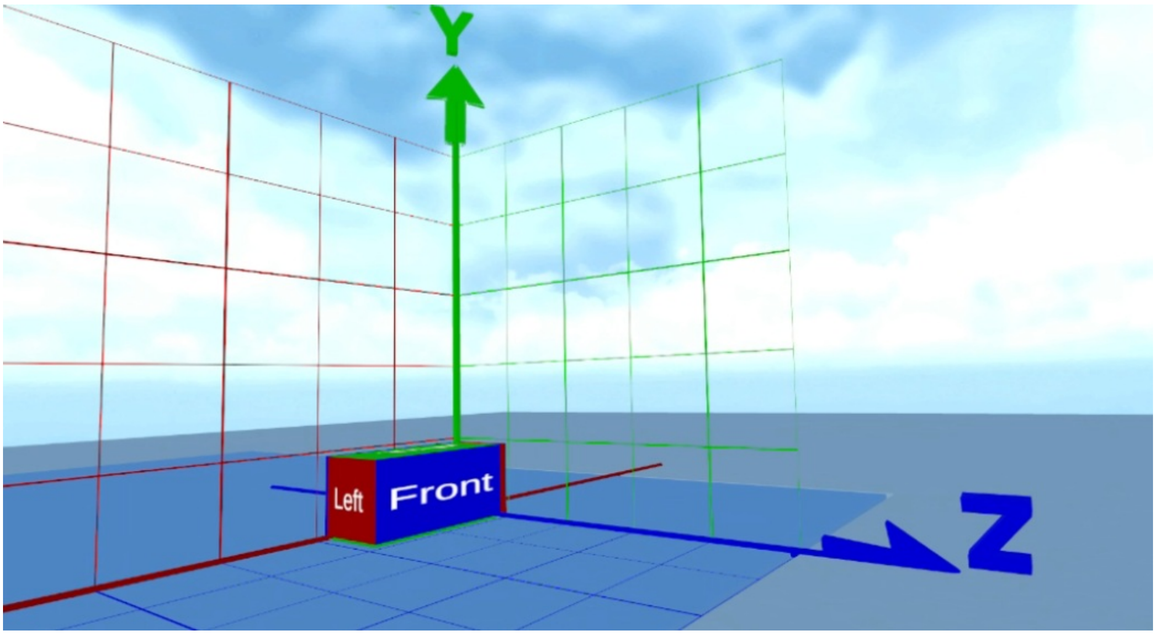
○ glRotatef(-45, 0, 1, 0)

○ glRotatef(-45, 0, 0, 1)

○ glRotatef(45, 1, 0, 0)

* Write OpenGL command if you want to rotate an object by 90 degrees anti-clockwise around the Z-axis.

* Which of the following OpenGL commands executing that scene?



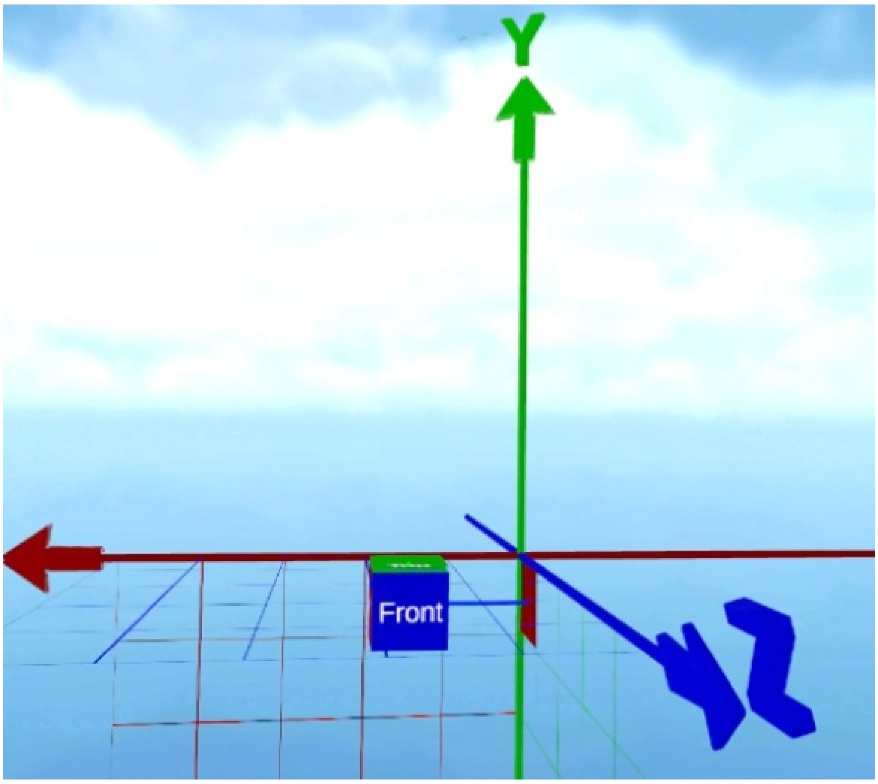
○ glScalef(1, 2, 1)

○ glScalef(2, 1, 1)

○ glScalef(2, 2, 2)

○ glScalef(1, 1, 2)

* Which of the following OpenGL commands executing that scene?



○ glTranslatef(1, 1, 0)

○ glTranslatef(-1, 1, 0)

○ glTranslatef(1, -1, 0)

○ glTranslatef(0, -1, 1)

* How do you find the immersive VR environment for improving learning of 3D transformations ?

* What aspects of the VR learning experience contributed most to your engagement or lack thereof?

* Overall, how satisfied are you with the immersive VR environment for learning 3D transformations and enhancing spatial visualization skills?

○ Very satisfied

○ Satisfied

○ Neither satisfied nor dissatisfied

○ Dissatisfied

○ Very dissatisfied

1. Background Information

This survey aims to gather expert feedback on the appropriateness, educational effectiveness, and usability of the VR content designed to learn 3D transformations and enhance spatial visualization skills in computer graphics.

* Position:

○ Teaching Assistant
○ Lecturer
○ Assistant Professor
○ Associate Professor
○ Professor

* Years of Experience in Education:

☐

* Your Field of Expertise:

☐

2. Educational Effectiveness

* The complexity of 3D transformations (e.g., translation, rotation, scaling) in the VR environment is appropriate for student learning.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* The 3D transformations in the VR environment effectively support students in understanding these concepts.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* Seeing real-time changes in the VR environment helps me understand OpenGL 3D transformations better.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* Using the VR environment improves students' spatial visualization skills.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

3. Interface Usability

* The visual representation of 3D transformations in the VR environment is clear and easy to interpret.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* The VR interface is intuitive for performing basic transformations, such as translation, rotation, and scaling.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* The VR interface is intuitive for applying multiple transformations in sequence.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* Does the immersive VR experience enhance spatial visualization skills?

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* Are the interactive features (e.g., manipulable objects, real-time feedback) helpful for learning 3D transformations?

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

4. Interactivity and Engagement

* The interactive features of the VR environment (e.g., object manipulation, real-time feedback) keep students actively engaged during learning.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* The use of head movement and navigation in VR enhances students’ perception of 3D space.

○ Strongly agree
○ Agree
○ Neither agree nor disagree
○ Disagree
○ Strongly disagree

* The interactive elements in the VR environment (e.g., manipulable objects, real-time feedback) are helpful for learning 3D transformations.

○ Strongly agree

○ Agree

○ Neither agree nor disagree

○ Disagree

○ Strongly disagree

5. Comments and Suggestions

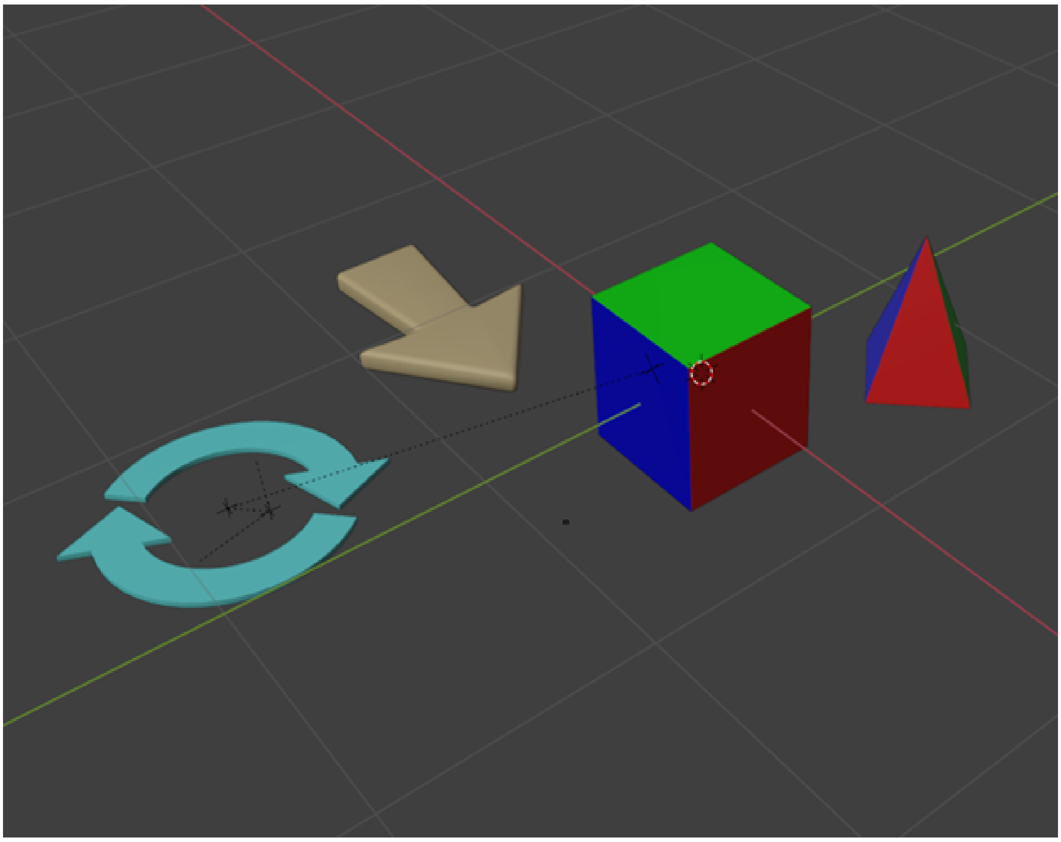
Please provide any additional comments or suggestions to improve the immersive virtual environment in learning.

Appendix C

Environment Development

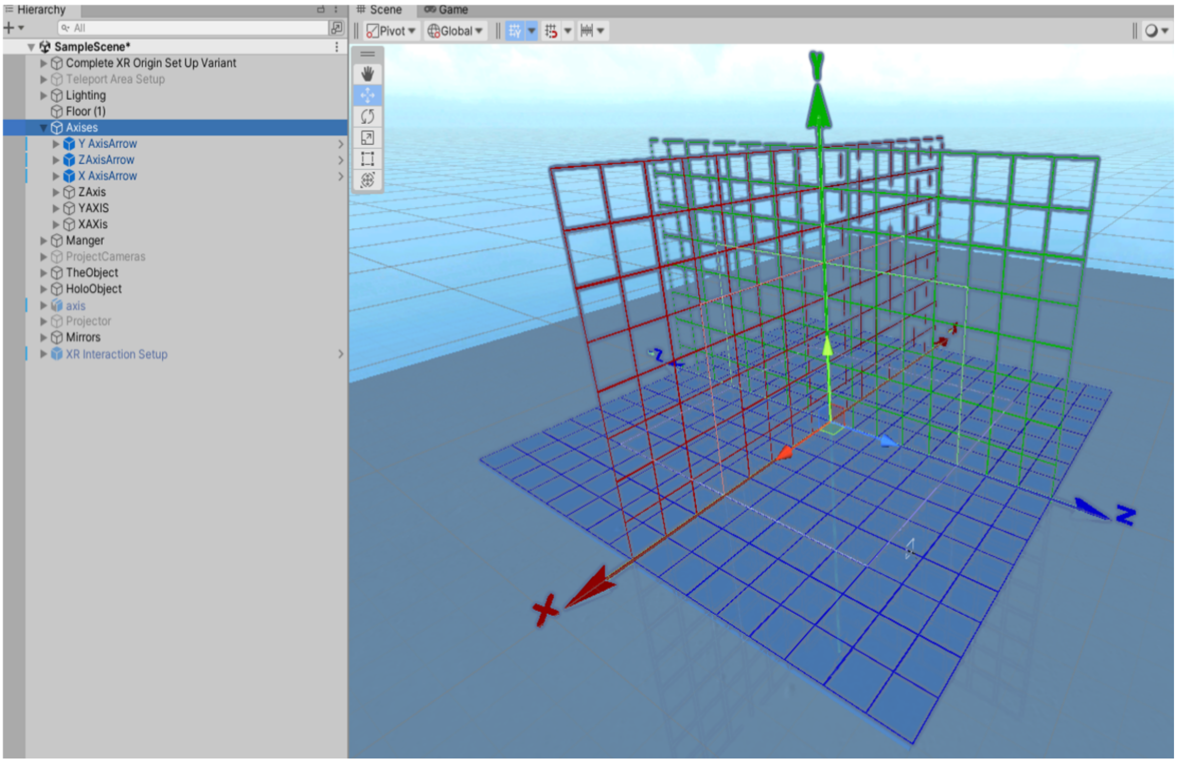
C.1 Design the models with blender

The models designed with blender as separate meshes with different materials to each mesh, so they can edit easily on unity.



C.2 Import the models and build the scene

The scene is based on the template, with the addition of a grid model (a plane with a grid texture) and coordinate axes, both designed in Blender. These elements are grouped under a single object named Axises.



C.3 System Design Overview

The core system is designed around the Commander design pattern, in which a central Commander component coordinates the operation of the various subsystems. This architecture ensures modularity, maintainability, and clear separation of responsibilities among components.

Primary System Components:

- Object Controller

  Responsible for managing the visibility of 3D meshes, determining which objects should be displayed or hidden in the scene.

- Function Applier

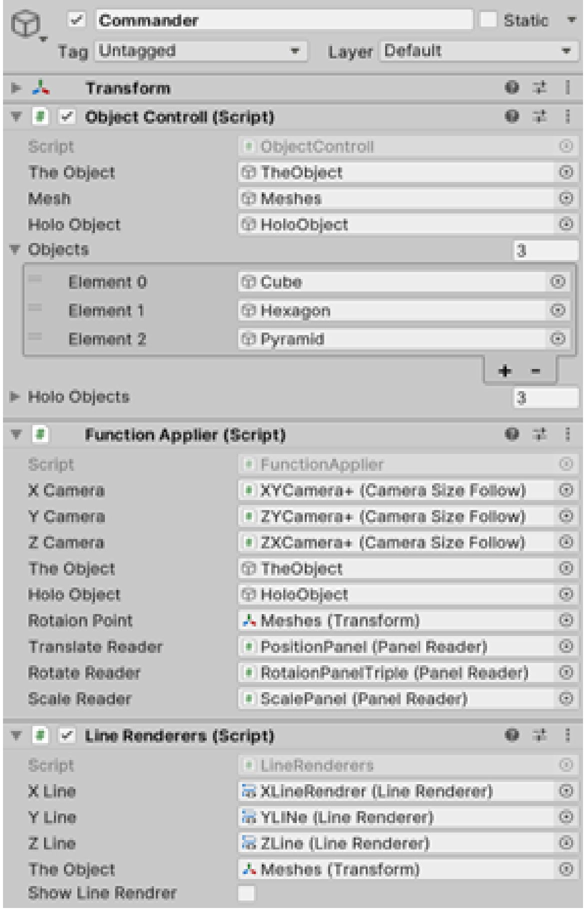
  Executes transformation operations, including translation, rotation, and scaling, on target objects according to user input or system commands.

- Line Renderer

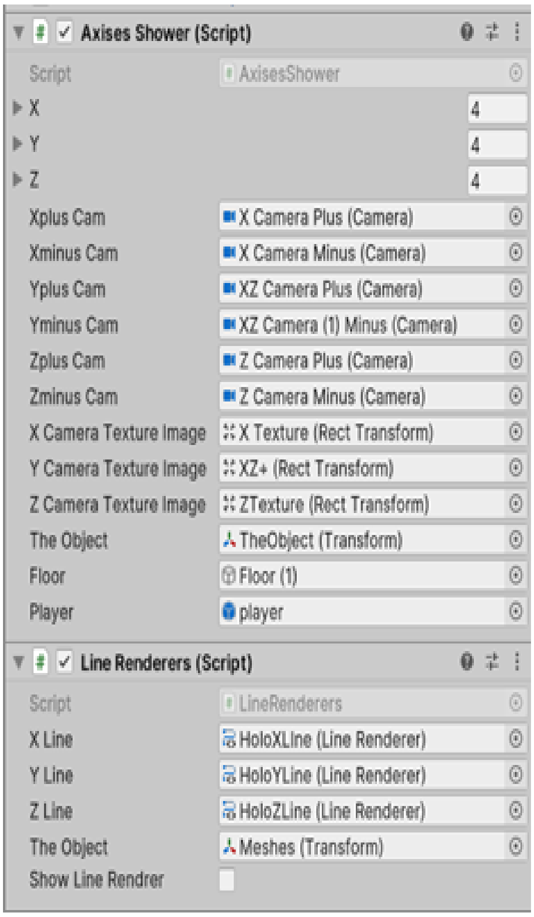
  Manages the rendering of visual line effects that connect objects to their corresponding axis planes, providing visual cues for spatial relationships.

- Axes Shower

  Determines which elements of the coordinate axes are visible, enabling or disabling axis components as required for the interaction or instructional context.



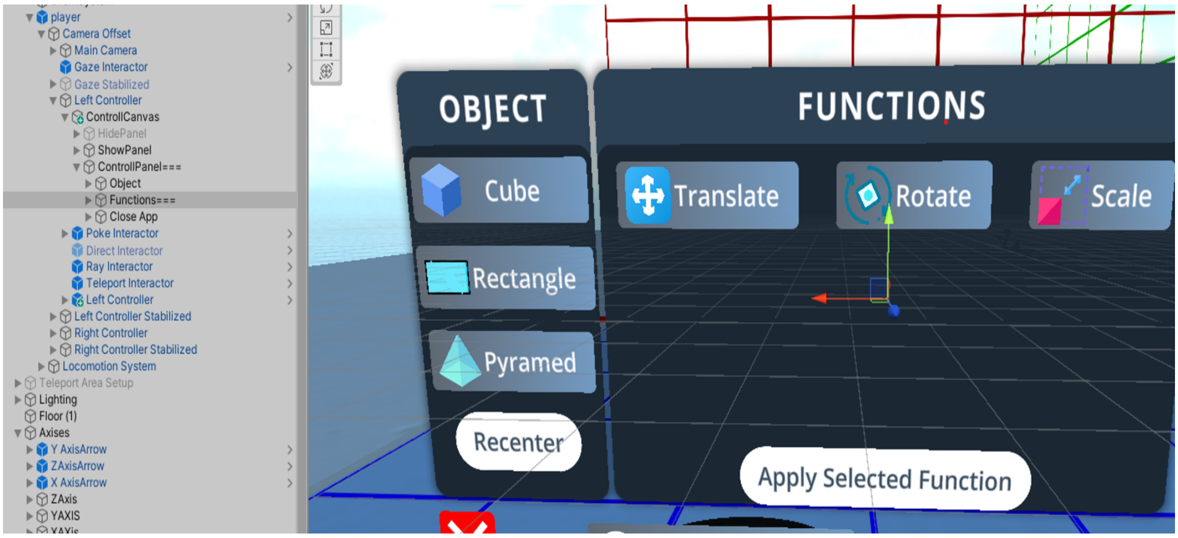
☑ Commander	☐ Static
Tag	Untagged
Layer	Default
Transform	
☑ Object Controll (Script)	
Script	ObjectControll
The Object	TheObject
Mesh	Meshes
Holo Object	HoloObject
Objects	3
Element 0	Cube
Element 1	Hexagon
Element 2	Pyramid
Holo Objects	3
Function Applier (Script)	
Script	FunctionApplier
X Camera	XYCamera+ (Camera Size Follow)
Y Camera	ZYCamera+ (Camera Size Follow)
Z Camera	ZXCamera+ (Camera Size Follow)
The Object	TheObject
Holo Object	HoloObject
Rotaion Point	Meshes (Transform)
Translate Reader	PositionPanel (Panel Reader)
Rotate Reader	RotaionPanelTriple (Panel Reader)
Scale Reader	ScalePanel (Panel Reader)
☑ Line Renderers (Script)	
Script	LineRenderers
X Line	XLineRendrer (Line Renderer)
Y Line	YLINe (Line Renderer)
Z Line	ZLine (Line Renderer)
The Object	Meshes (Transform)
Show Line Rendrer	☐



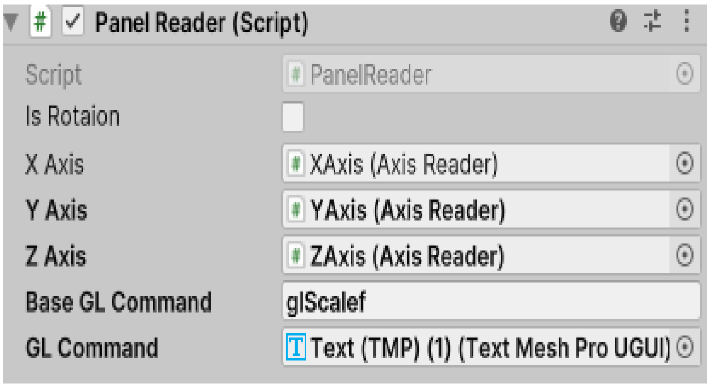
☑ Axises Shower (Script)	
Script	AxisesShower
X	4
Y	4
Z	4
Xplus Cam	X Camera Plus (Camera)
Xminus Cam	X Camera Minus (Camera)
Yplus Cam	XZ Camera Plus (Camera)
Yminus Cam	XZ Camera (1) Minus (Camera)
Zplus Cam	Z Camera Plus (Camera)
Zminus Cam	Z Camera Minus (Camera)
X Camera Texture Image	X Texture (Rect Transform)
Y Camera Texture Image	XZ+ (Rect Transform)
Z Camera Texture Image	ZTexture (Rect Transform)
The Object	TheObject (Transform)
Floor	Floor (1)
Player	player
☑ Line Renderers (Script)	
Script	LineRenderers
X Line	HoloXLine (Line Renderer)
Y Line	HoloYLine (Line Renderer)
Z Line	HoloZLine (Line Renderer)
The Object	Meshes (Transform)
Show Line Rendrer	☐

C.4 Design the UI Canvases

The system includes a single UI Canvas, named Control Canvas, attached to the player's left hand. It is implemented using the Unity UI system and is designed to meet the requirements.



The Control Canvas contains scripts called Axis Readers that capture user input, along with panels that present and organize interface elements.



Panel Reader (Script)

Script	PanelReader
Is Rotaion	☐
X Axis	XAxis (Axis Reader)
Y Axis	YAxis (Axis Reader)
Z Axis	ZAxis (Axis Reader)
Base GL Command	glScalef
GL Command	Text (TMP) (1) (Text Mesh Pro UGUI)

C.5 Implementation of OpenGL Functions

The function implementation process occurs within the commanders of the Function Applier module, which is responsible for two primary tasks.

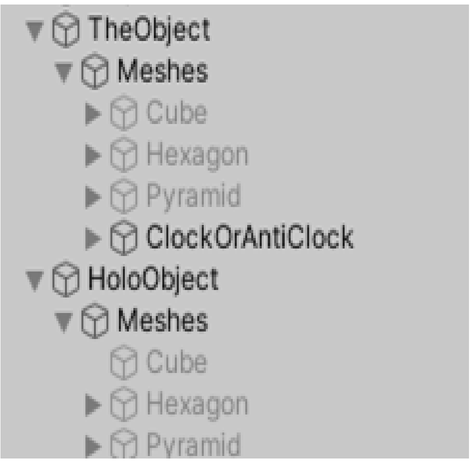
1. Check what function to apply from the user input.

2. Apply the function to the object.

```
IEnumerator SmoothTranslate(GameObject obj)
{
    Vector3 target = TranslateReader.getPanelValues();
    Vector3 start = obj.transform.position;
    float time = 0;
    while (time < 1)
    {
        time += Time.deltaTime;
        obj.transform.position = Vector3.Lerp(start, target, time);
        yield return null;
    }
}
private void ApplyRotateFunction(GameObject obj)
{
    RotaionPoint = obj.transform.GetChild(0);
    Vector3 target = RotateReader.getPanelValues() * -1;
    Vector3 start = RotaionPoint.transform.rotation.eulerAngles;
    RotaionPoint.transform.rotation = Quaternion.Euler(target);
}
private void ApplyScaleFunction(GameObject obj)
{
    Vector3 target = ScaleReader.getPanelValues();
    obj.transform.localScale = target;
}
```

C.6 Implement the Visual Effects

To implement the visual effects, a duplicate of the main game object was created to serve as a visual copy. This approach results in multiple copies being present within the line renderer's hierarchy. The Unity Line Renderer component was utilized to create a visual line effect extending from the object to the plane. Additionally, a holographic effect was achieved by applying a transparent material to the visual elements.



C.7 Implement the Reflections

Reflections (mirrors in the panels) were implemented using Unity's Render Texture feature combined with six cameras. This technique allows for real-time rendering of reflections on surfaces.

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