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Mixed Reality as a Teaching Tool for Improving Spatial Visualization in Engineering Students

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Abstract

Perceiving experiences can be achieved through various channels of reception, where learners receive information in diverse styles, e.g., visualizing and hearing, reflecting and acting, reasoning logically and intuitively, and memorizing. Among all these perceiving ways, visualization has been receiving significant attention in STEM learning due to its ability to support learners in constructing large and intricate information structures, making them more comprehensible. One form of visualization, spatial visualization or spatial-visual ability, is a compound operation that integrates visual perception and mental imagery. Spatial visualization skills involve the ability to mentally maneuver two-dimensional and three-dimensional objects. These skills are crucial for learners in STEM disciplines in general, with a particular emphasis on their significance for engineering students. Research studies reveal that the lack of spatial visualization skills negatively impacts engineering students' educational and psychological performance. Thus, this work aims to explore how Mixed Reality (MR) can be used as a pedagogic tool to develop students' spatial visualization skills. Throughout this work, an interactive MR module on hydraulic gripper designs is developed and tested in undergraduate courses. The MR module comprises a 10-minute tutorial session and a 20-minute interactive simulation lab on hydraulic grippers. It exposes students to virtual object manipulation and spatial interactions in MR settings, allowing them to visualize and interact with the internal structure of hydraulic grippers to help improve their spatial visualization skills. A research study is then conducted by incorporating the module into an undergraduate course to examine the effectiveness of MR as a teaching tool for developing students' spatial visualization skills. The Revised PSVT:R, a psychometric tool used to assess the level of improvement in the students' spatial skills, is utilized. Besides inspecting the effectiveness of MR in enhancing students' spatial visualization skills, the study also aims to investigate the impact of MR modules on students' motivation levels toward learning fluid power concepts. Therefore, self-reflection surveys consisting of Likert scale and semantic differential questions are designed to study students' learning experiences. The study findings showed that MR has the potential to improve students' spatial abilities, where the class average ability increased from 74% to 80%. This result can be further enhanced by exposing students to other MR labs, giving them more time to visualize 3D shapes in MR settings. The results also revealed a positive impact of MR on students' learning experience, as more than 94% showed interest in learning through MR modules.

Keywords: mixed reality, spatial visualization, motivation, learning

1. Introduction

Spatial visualization, also known as spatial-visual ability, is a compound operation that integrates visual perception and visual-mental imagery, allowing individuals to mentally visualize and manipulate three-dimensional (3D) objects [1]. This operation is achieved through three integrated processes: inspection, transformation, and maneuvering of images. Combining these three processes allows for depicting the mental manipulation of objects in a 3D space without employing the visual stimulus [2].

Developing spatial-visual ability is crucial in the conceptualization processes in STEM education involving cognitive thinking and the acquisition of abstract concepts [3]–[5]. Among all scientific fields, engineering disciplines require high spatial visualization proficiency [3], [6]. Success in fundamental engineering courses is highly associated with demonstrating high skills in designing, generating, and modeling 3D computer-aided design (CAD) layouts of complex systems, all requiring spatial abilities [7]. Engineering students must exhibit proficiency in implementing schematic tasks like orthographic projection, isometric drawings, assembly schematics, and analyzing and interpreting hidden and sectional views [8]. Such engineering skills necessitate high critical thinking and problem-solving abilities that are highly correlated to generic intelligence and cognitive eligibility [9]–[11]. To this end, the lack of spatial-visual abilities critically impacts engineering students' educational performance. Research studies reveal that 10 to 20% of engineering students struggling with poor spatial skills, face difficulties passing their technical courses [8], [12].

Besides significantly affecting their academic performance, deficient spatial visualization skills adversely affect students’ psychological health [13]. Students have varying natural abilities, with some intuitively excelling in spatial visualization. This range of perceptual skills causes dissatisfaction and frustration among students, especially those who lack spatial skills. Students feel discouraged at being unable to complete tasks that are easy for their colleagues. Consequently, the non-compatible level of perceptual skills among students will lead those with inadequate spatial abilities to shift away from disciplines that require solid cognitive skills [14], [15].

Therefore, the problem of spatial visualization requires conducting more research to explore and asses new teaching methods and techniques to improve spatial-visual skills across many engineering disciplines. For this reason, this work aims to investigate the impact of new digital technologies, like state-of-the-art Mixed Reality (MR), on enhancing the students’ spatial skills in the engineering technology discipline. It presents the use of MR technology as an immersive spatial visualization tool for exposing students to 3D visualization and object manipulation through interactive MR modules. Another objective is to examine the impact of incorporating MR as a teaching tool on students’ learning experiences and acquisition of engineering concepts.

The rest of this paper is organized as follows: Section 2 (Background) gives an overview of the existing methods educators utilize in engineering education to address the students’ spatial development skills. Section 3 (Proposed Methodology: MR for Spatial Visualization) presents our proposed methodology, using MR technology to develop spatial visualization skills. This section provides an overview of MR technology and its features, emphasizing its potential for enhancing the students’ spatial ability and learning experience. It also discusses the development of the MR module, its functionalities, and its capabilities. Section 4 (Study Design) presents the generated study, the adopted experimental design, and data collection tools. Section 5 (Study Findings) discusses the study’s outcomes and insights. Finally, in Section 6 (Conclusions and Future Work), the paper summarizes the essential findings and insights from the work.

2. Background

The significance of spatial visualization in engineering disciplines has summoned researchers and educators to adopt interactive teaching techniques for reinforcing students' spatial skills. Educators across different engineering fields have been exploring digital technologies, from web-based to immersive applications, to serve as spatial learning platforms, keeping pace with rapid technological advancements in education [16], [17].

2.1 Web-Based Applications for Improving Spatial Visualization

Some researchers have been developing and incorporating digital interactive web-based applications into engineering laboratories to reinforce the students' spatial abilities. For instance, a group of researchers developed an Interactive Learning Management System (ILMS) to be employed as a web-based launch assistant learning tool to develop spatial visualization skills for students throughout engineering drawing courses [18]. The ILMS application introduced students to the fundamentals of engineering drawing education, e.g., isometric and multi-view drawings, sectioning layouts, dimensioning tools, and orthographics. It comprised three main subsystems: preliminary level assessment test, interactive tutorials, and content management configuration, allowing instructors to track the students' progress. Researchers conducted a two-year study on engineering graphics students at the University of Burgos in Spain to test the effectiveness of ILMS compared to traditional learning methods [19]. They designed 55 survey modules using the questionnaire planning criteria in [20], [21]. Their study findings proved the effectiveness of the ILMS web-based application in assisting students with no prior knowledge of technical drawing. However, the results did not demonstrate a significant advantage of the application over traditional learning methods, indicating a need for substantial improvements. Examiners highlighted issues with the quality of visual aids, including videos, audio, and animations, which were deemed chaotic.

Similar to the ILMS application, other spatial-visual aid websites were developed by various universities to improve their students' spatial skills [22]–[25]. For instance, the University of Massachusetts at Amherst created an online tutoring application to support students while working with orthographic and isometric views [24]. The application taught students visualization techniques for constructing images of objects from their orthographic projections and vice versa. Similarly, Pennsylvania State University generated a Visualization Assessment and Training online platform to help students comprehend and improve their spatial visualization abilities. The platform involved three interactive activities: 3D block rotation, paper folding, and water-level visualization. Adding to the above universities, Michigan Technological University, Ireland's University of Limerick, and the University of Texas-Pan American have also designed similar online web-based applications to reinforce spatial visualization skills for engineering students [26].

2.2 Immersive Applications: Virtual and Augmented Realities

Other educators adopted more immersive digital technologies like virtual reality (VR) and augmented reality (AR) as pedagogical tools to tackle the problem of spatial visualization [27], [28]. VR is the technology that creates a simulated environment, immersing users in a realistic virtual world that can be explored using computer-generated sensory experiences [29], [30]. This technology has been excessively employed as a spatial visualization tool, given its ability to expose users to complex 3D graphics within a VR setting that mimics real-world scenarios [31]–[36].

In a comprehensive 10-year review of research on VR applications [37], findings revealed the efficacy of VR in addressing spatial visualization challenges. VR proved effective in simplifying theoretical concepts and navigating the intricacies of real-world representations. Despite its engaging features and effectiveness as a spatial visual tool, VR has technical limitations associated with real-time feedback, image quality, and motion sickness [38], [39]. VR has issues accurately recognizing image resemblances and assessing the degree of image distortion. Alongside these technical concerns, prolonged exposure to immersive VR environments (more than 10 minutes) leads to motion sickness and discomfort, causing severe headaches, nausea, eyestrain, and disorientation [40], [41]. Studies show that up to 80% of VR users experience motion sickness 10 minutes after exposure to the VR environment [42], [43].

Unlike VR, which disconnects the user from the physical world, AR provides a new virtual experience by presenting virtual objects into the real world [44], [45]. AR allows overlaying digital objects in the real world via smart devices, like phones, screens, or displays, which are widely available and affordable [46]. Also, it enables addressing VR-related issues, albeit with limitations related to motion sickness and discomfort. Given its accessibility and features, AR has been used as a spatial tool in engineering curricula to develop students' cognitive reasoning and assist in acquiring fundamental engineering concepts [47]–[49]. For instance, in [48], a group of scholars at the University of Tecnológico de Monterrey in Mexico developed an AR application to be used as a spatial visualization promoter in learning Calculus for engineering students. The application permitted students to visualize the 3D projections of three math functions, like parabolas, sine waves, and circular surfaces, by augmenting math functions as tangible 3D virtual objects. Moreover, the application allowed users to conceive the entire executed perceptible visual process, i.e., constructing the intended virtual shape. Educational AR applications successfully improved the students' spatial reasoning and learning experience while addressing issues emerging from VR environments [50], [51]. However, despite these positive outcomes, results revealed that AR technology is less immersive when compared to VR, as it lacks the level of presence/depth and interactive capabilities [52].

The limitations of VR and AR call to address the problem of spatial reasoning in engineering courses by exploring more immersive digital technologies that combine the features of both. Therefore, this work investigates the effectiveness of MR technology in improving mechanical engineering technology (MET) students' spatial skills and overall learning experience.

3. Proposed Methodology: MR for Spatial Visualization

An interactive MR module on hydraulic actuated grippers' internal structure visualization and design is developed to test students' spatial skills in Fluid Power courses. The following subsections provide an overview of MR technology and its features and discuss the development and capabilities of the developed MR module.

3.1 Exploration of MR Technology: Features and Functionalities

MR technology, known as the fourth-coming evolution in the human-machine interface, seamlessly integrates the features and capabilities of VR and AR while avoiding the technical issues associated with each [53]. It creates an immersive, interactive environment that merges digital content with the physical world, enabling users to interact with and manipulate digital objects in real-time within their physical surroundings. Its ability to cohesively integrate virtual and augmented elements provides users with experiences ranging from fully virtual to entirely physical [54].

MR employs advanced spatial algorithms, like spatial mapping [55], spatial awareness [56], and spatial anchor [57], that allow spatially superimposing interactive digital content onto the physical world while analyzing the user's physical actions. Besides the spatial algorithms, MR uses real-time tracking packages to track the user's movements and monitor the dynamic integration of computer-generated information [58]. MR experience is achieved through advanced holographic headsets, like Magic Leap [59] and Microsoft Hololens [60], [61], that enhance display quality and eliminate the motion sickness experienced in VR.

Given its features and capabilities, MR technology has been serving engineering education by improving engineering training, problem-solving, and thus students' overall learning experience [62]–[66]. Besides being an educational tool, MR can be an effective spatial visual tool. Its interdisciplinary nature increases its potential for reinforcing students' spatial skills while engaging them in interactive, realistic modules. For this reason, an engaging MR module pivoted on hydraulic systems is designed and incorporated into fluid power course laboratories to test the effectiveness of this technology in addressing spatial visualization problems.

3.2 Interactive MR Module Development

The MR module is developed for undergraduate MET students, utilizing Microsoft-driven Mixed Reality Tool Kit 2 (MRTK2) and OpenXR Plugin for Unity with HoloLens 2. The module is designed to enhance students' spatial skills and assist them in acquiring fundamental fluid power concepts. It comprises a ***10-minute tutorial session*** and a ***20-minute hydraulic simulation lab*** in MR settings. The 10-minute tutorial teaches students basic MR hand manipulation techniques and exposes them to different spatial 3D shape interactions in MR settings, thus preparing them for the simulation lab. The 20-minute simulation lab familiarizes students with two categories of hydraulic grippers (light-duty and heavy-duty), allowing for the visualization of their internal structure, the study of subsystem assembly, and testing mechanisms. The module is designed in four stages (Stage 1: Spatial 3D Shapes Design and Animation, Stage 2: Gripper Design, Stage 3: MR Scenes Setup/Design, and Stage 4: Module Technical Testing), as illustrated in the diagram in Figure 1.

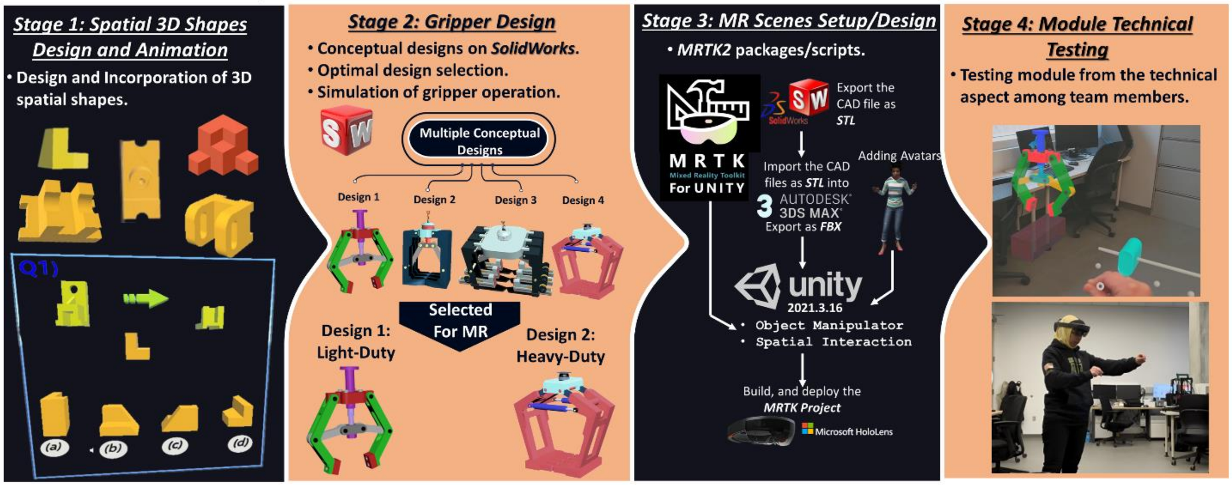


Figure 1. Diagram illustrating the four stages of the MR module design

Stage 1 focuses on designing and animating 3D spatial questions with varying levels of difficulties for exposing students to spatial visualization techniques throughout the MR tutorial session. Throughout this stage, up to 10 distinct 3D spatial shapes are designed using SolidWorks. The shapes are then used to develop six spatial visualization ability questions using the psychometric properties of the Revised Purdue Spatial Visualization Test – Rotation (Revised PSVT:R) test [67]. The psychometric properties of the PSVT: R helped ensure the reliability and validity of the questions in assessing students' mental ability to manipulate and understand spatial relationships in MR settings.

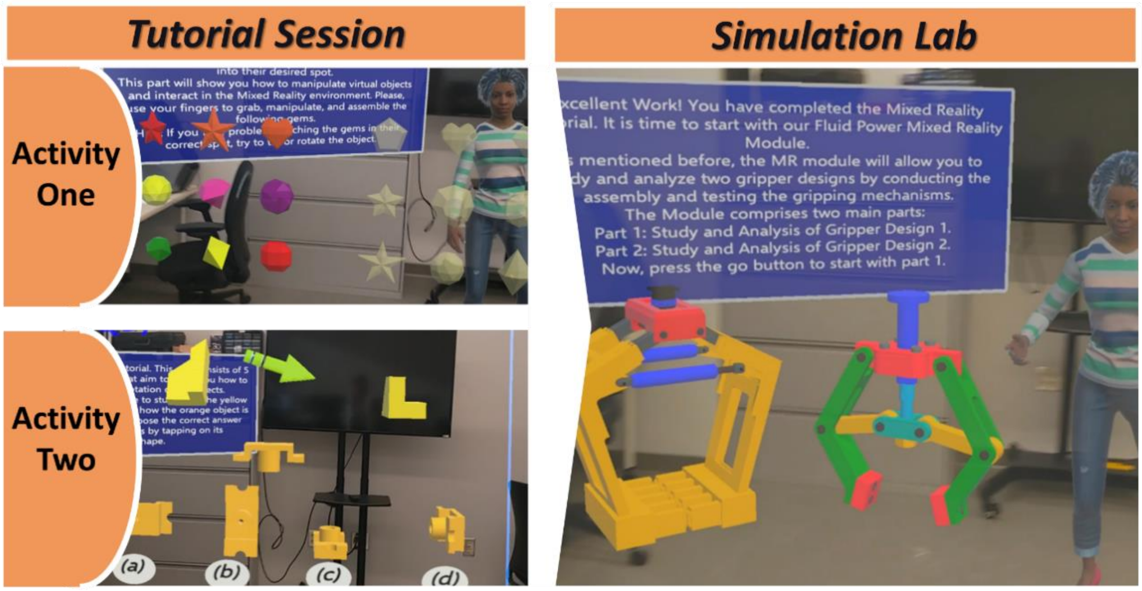
Following stage 1, **stage 2** is pivoted on developing conceptual designs for light-duty and heavy-duty hydraulic grippers and selecting the optimal designs for the MR hydraulic simulation lab. Four hydraulic gripper CAD models incorporating various mechanisms and subsystems are designed and simulated using SolidWorks. Then, the two optimal models are selected for the MR simulation lab based on the complexity of the designs and the Fluid Power course learning outcomes.

Stage 3 is the core phase of the MR module development, as it focuses on setting up and designing the required MR scenes involving the tutorial session and simulation lab. Throughout this stage, Unity software, a cross-platform game engine developed by Unity Technologies [68], is employed along with MRTK for Unity, a Microsoft-driven platform [69], and other platforms to create a realistic MR experience. For preparing the MR scenes, the required MRTK 2 packages (MRTK2 Extensions, MRTK2 Foundations, MRTK2 Test Utilities, MRTK2 Tools, etc) are installed and imported into Unity using the Mixed Reality Feature Tool for Unity [70]. After setting the MR scenes, the 3D spatial shapes and gripper CAD STL models developed through stages 1 and 2 are converted from STL to FBX supported by Unity using 3ds max. Then, the FBX models are imported into Unity as GameObject assets, including Avatar characters serving as virtual agents to provide guidance throughout the module. MR Unity scripts are developed and incorporated into the Unity assets using built-in UnityEngine and MRTK namespaces, like `(UnityEngine.Events)`, `(Microsoft.MixedReality.Toolkit.UI)`, `(Microsoft.MixedReality.Toolkit.Input)`. The developed scripts allow for near and far interactions with virtual assets, like grabbing, rotating, and manipulating MR objects. The scripts also allow spatial mapping, spatial awareness, eye/hand tracking, and user UI controls. The MR module, including the 10-minute tutorial session and 20-minute simulation, is then built and deployed as a Unity application on the holographic device HoloLen2 manufactured by Microsoft.

Finally, **stage 4** is based on testing the technical aspects of the MR module. In this stage, the module is tested by technical MR developers and experts, ensuring it meets the highest standards in terms of performance, user experience, and technical functionality. The testing procedure involved various elements. It assessed the level of immersion, quality of the displayed content (graphics, textures, and overall visual fidelity), and accuracy and reliability of hand/eye tracking. Also, the responsiveness to user actions is examined to ensure a seamless and intuitive interaction, like responses to user gestures or voice commands.

3.3 MR Module Capabilities

As previously mentioned, the MR module consists of a 10-minute tutorial session on MR technology and a 20-minute simulation lab on hydraulic grippers. The tutorial session introduces students to MR features and visualization methods, and the simulation lab exposes students to the gripper's internal structure, assembly, and operation, as shown in Figure 2.



into their desired spot.
This part will show you how to manipulate virtual objects and interact in the Mixed Reality environment. Please, use your fingers to grab, manipulate, and assemble the following gems.
If you … proble… …ching the gems in their correct sp…t, try to … or rotate the object.

xcellent Work! You have completed the Mixed Reality
rial. It is time to start with our Fluid Power Mixed Reality Module.
s mentioned before, the MR module will allow you to
dy and analyze two gripper designs by conducting the assembly and testing the gripping mechanisms.
The Module comprises two main parts:
Part 1: Study and Analysis of Gripper Design 1.
Part 2: Study and Analysis of Gripper Design 2.
Now, press the go button to start with part 1.

Figure 2. Basic capabilities of the MR module

The tutorial session comprises two main activities (Activity 1: Object Manipulation and Activity 2: Spatial Visualization). **Activity one** aims to introduce students to the fundamental manipulation techniques in MR settings, exposing them to the MR features and familiarizing them with different interaction methods. During this activity, students are guided through various methods of interacting with virtual objects in an MR environment, like hand gestures, voice commands, spatial anchors, and other MR interaction functions. After completing this activity, students are expected to be comfortable and proficient in interacting with virtual objects and ready to go through activity two. **Activity two** exposes students to the six spatial visualization ability questions developed using the psychometric properties of the Revised PSVT: R test. Students are asked to answer the questions in an MR setting by having them visualize and interpret the rotation of 3D objects. For each question, students need to visualize and study the rotation of the animated yellow object and mentally picture the rotation of the orange object accordingly (see Figure 3). Then, students choose the correct solution from the four possible options by tapping its corresponding shape. As shown in Figure 3, visual and hearing aids, e.g., animations, color change, and voice commands, are utilized through this activity to enhance the user's experience. The goal of the visual and hearing aids is to provide immediate feedback in real-time after choosing an option, notifying the student whether their answer is correct or not. Therefore, this activity enhances the students' cognitive and spatial reasoning skills, preparing them for the simulation lab.

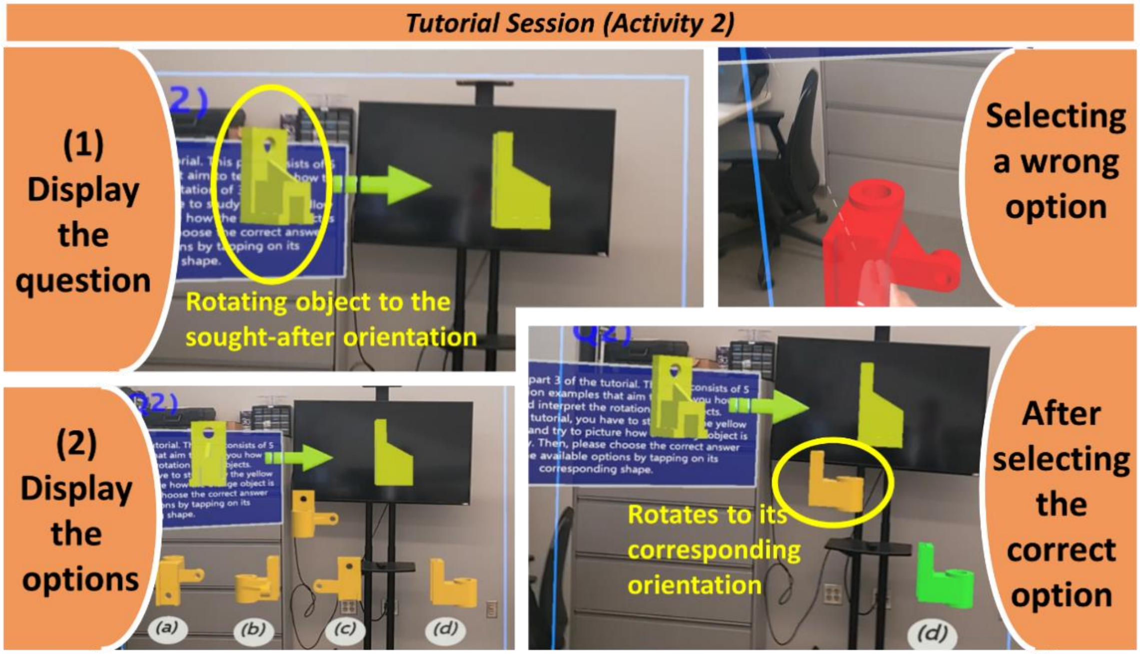


Figure 3. One of the six spatial ability questions in Activity two

After completing the 10-minute tutorial, the virtual avatar guides the students to the simulation lab to experience the two grippers (light-duty and heavy-duty). Students must complete three main tasks for the gripper: Task 1: Study the internal structure for the gripper design, Task 2: Generate the assembly, and Task 3: Test the associated mechanism (see Figure 4).

Figure 4 shows the three required tasks for the heavy-duty and light-duty grippers. **Task one** (study and visualization of the grippers' designs) allows the students to interact virtually with the grippers' components using hand and object manipulation techniques introduced in the tutorial session. Detailed technical information and specifications for the components are presented upon interaction. After completing task 1, **task two** (assemblies) permits the students to assemble the grippers in a pre-defined sequence, learning and understanding the gripper's designs. Finally, **task three (**mechanism testing) allows students to study the grippers' operation through virtual UI controls. Visual indications, such as color changes, are employed throughout the simulation lab to enhance user experience and provide immediate feedback.

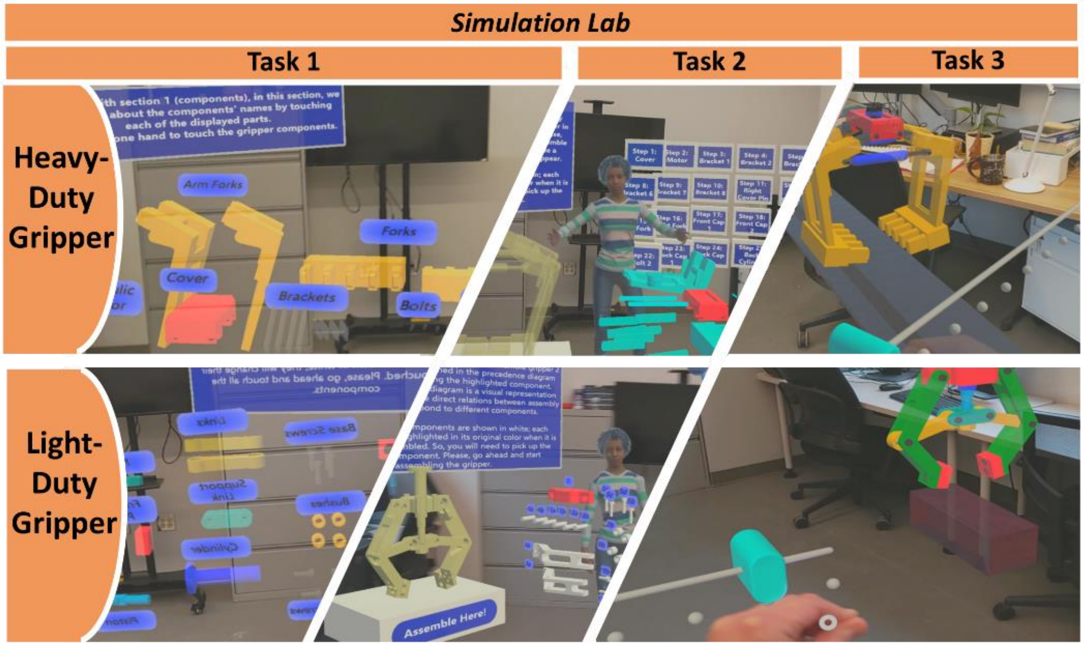


Figure 4. Studying the hydraulic grippers in an MR setting

4. Study Design

The module is integrated within an undergraduate Fluid Power course to be experienced by MET students. An institutional review board (IRB) application is approved, and a research study is conducted with 102 students enrolled in the course. The Revised PSVT:R, developed and provided by Purdue University, is employed to assess the variation in the students' level of spatial skills. Besides the Revised PSVT:R test, surveys have been designed to test the improvement in students' learning pre-and-post experiencing the MR module and measure their internal perspective toward MR technology. All students enrolled in the Fluid Power course experienced the MR module and completed the Revised PSVT:R test during one of their MET:230 lab sessions. However, only 90 students out of the 102 completed the surveys two weeks after experiencing the MR lab. The following subsections introduce the adopted data collection tool and the experimental design and reveal the ultimate results of the study.

4.1 Data Collection Tools

Two data collection tools are utilized throughout the research study: Revised PSVT: R test provided by Purdue University and surveys designed by the research team.

4.1.1 Revised PSVT: R Assessment Tool

The Revised PSVT:R is a cognitive test designed to assess students' spatial visualization abilities, i.e., their ability to mentally rotate 3D objects [67]. It serves as a psychometric tool used by various researchers to examine the spatial-visual skills of students aged 13 and above in multiple academic disciplines [71]. The Revised PSVT:R comprises 30 multiple choice questions (MCQ) involving 13 symmetrical and 17 asymmetrical isometric view figures of 3D objects in their original and rotated sights. Figure 5 shows a sample of one of the questions requiring students to match the object's correct rotational shape. Given its eligibility to examine spatial skills, this test is used in our study to assess the enhancement of spatial skills among students, thus predicting their success in the course.

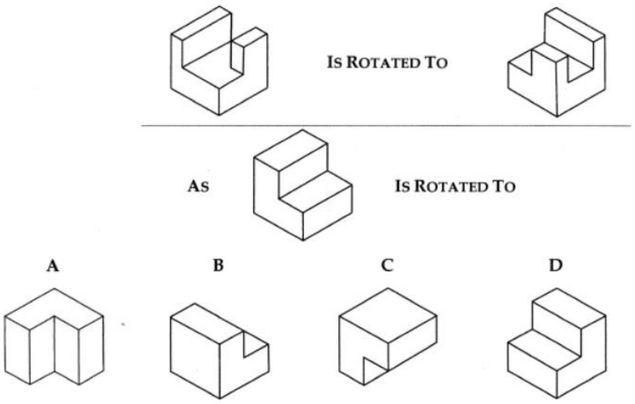


Figure 5. Sample for one of the questions of the Revised PSVT:R test [67]

4.1.2 Self-Reflection Surveys

Besides the Revised PSVT:R for assessing spatial ability, quantitative self-reflection surveys have been designed to evaluate the effectiveness of using MR technology as a pedagogical tool in engineering education. The self-reflection surveys in Table 1 comprise seven Likert scale questions and three semantic differential questions.

The data acquired by the Likert scale questions are based on a 5-point bipolar scale (5: Strongly Agree, 4: Agree, 3: Neither Nor, 2: Disagree, and 1: Strongly Disagree). The data collected by the semantic differential are also based on a 1 to 5 bipolar scale rating (5: Very Likely, 4: Likely, 3: Neutral, 2: Unlikely, and 1: Very Unlikely).

The Likert scale questions (Q1 to Q7) measure the students' internal beliefs toward different aspects of the MR module. They provide deeper insight into their perspectives, enabling a comprehensive analysis of their experiences. The first three Likert scale questions (Q1, Q2, and Q3) aim to measure the students' attitudes toward their confidence in their spatial abilities after conducting the MR lab. The rest of the Likert scale (Q4, Q5, Q6, and Q7) allows for examining the students' internal perspectives toward using MR for teaching modeling and simulations. The semantic differential questions (Q8 to Q10) measure the connotative meaning behind the proposed methodology, using MR as a spatial tool and teaching engineering concepts. These questions assess the qualitative aspects of students' thoughts/feelings, providing an understanding of subjective perceptions and attitudes toward our new teaching methodology.

Table 1. Survey questions designed by the team

#	**Question**	**Anchors of the Scale**
Self-Reflection Likert scale Questions		
Visualization and Spatial Abilities		1 = Strongly Disagree, 5 = Strongly Agree
Q1	The MR module helped in enhancing my spatial reasoning of diagnosis and problem-solving of hydraulic systems.	
Q2	The lab helped me visualize the hydraulic grippers' internal structure perceptibly.	
Q3	I was engaged in the MR lab, where I felt that the virtual hydraulic components presented in the MR environment really existed in the room.	
Engineering		
Q4	I can make better engineering decisions based on the skillset that I have acquired in the MR lab.	
Q5	My experience in the MR simulation stimulated my enthusiasm for engineering.	
Q6	My experience in the MR simulation increased my confidence in my ability to practice engineering.	
Q7	This mixed reality lab helped me reflect on my own understanding.	
Self-Reflection Semantic Differential Questions		
Q8	Given your experience with the MR labs, how likely are you to recommend MR simulation-based learning to other colleagues?	1 = Very Unlikely, 5 = Very Likely
Q9	How much did you like learning through mixed reality modules?	
Q10	How much did you like your overall experience?	

4.2. Experimental Study

The study framework is administrated as follows. MET:230 course involves a total of 102 students, distributed across seven sections, each consisting of 14 to 15 students. The 15 students per section have been divided into four groups, each comprising three to four students. This resulted in around 28 groups over the seven sections. All 102 students took the Revised PSVT: R test one week before experiencing the modules, where they were asked to solve the 30 questions in 30 minutes during lecture time under the supervision of the course instructor.

One week after completing the revised PSVT:R, students experienced the MR module, where six MR Microsoft HoloLens2 headsets were used throughout. Completing all the requirements and activities of the MR module, including the tutorial and simulation lab, takes 30 to 40 minutes, and the overall session time is two hours. Given the number of MR headsets and session time, the study was generated in 28 experiments over the seven sections in two consecutive weeks (around 14 experiments each week). The MR lab requires an unoccupied space to allow students to visualize and interact with the virtual assets independently in their scene without distractions from their peers and lab instructors. For this reason, two empty rooms at Dudley Hall were reserved to conduct the MR study. This arrangement allowed the four students per group to be divided into two empty rooms (two students per room) to experience the MR module, each in their scene, avoiding distraction by their peers' movements/ voices while conducting the lab (see Figure 6).

Thus, two experiments have been generated back to back each week in each of the seven sections. Each experiment required four MR headsets (the other two on charge) for the four students who experienced the MR module simultaneously but independently, i.e., each student in their scene. Figure 6 shows the four students per group experiencing the MR module within one of the sections divided into two empty rooms.

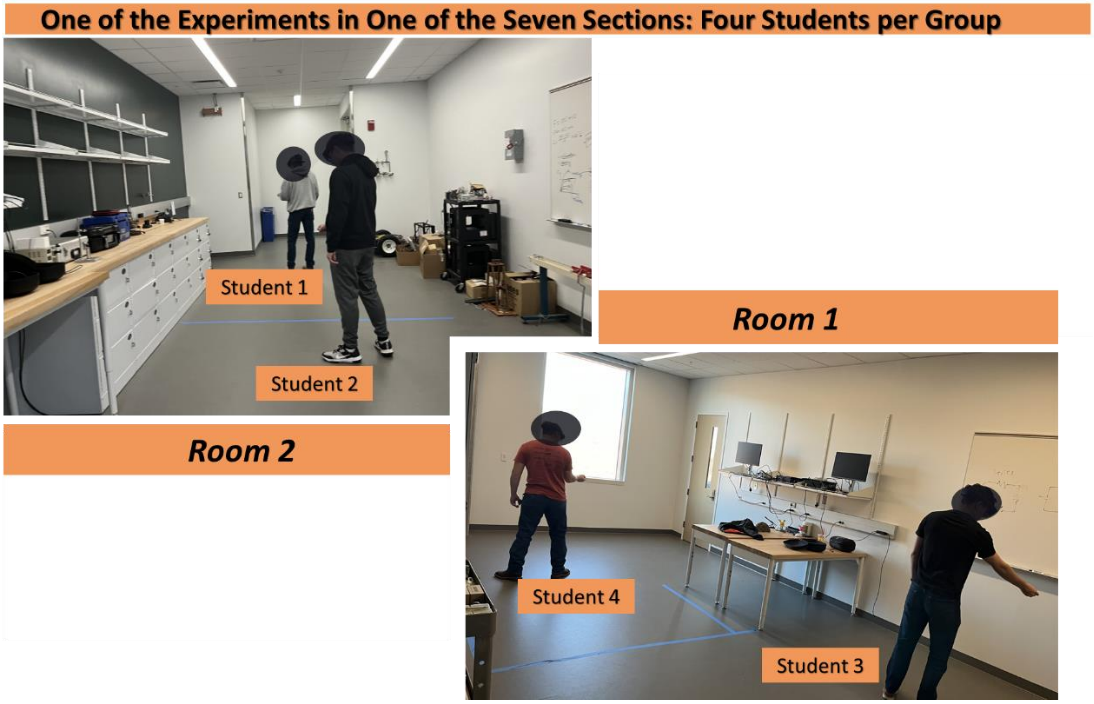


Figure 6. One group (four students) in one of the seven sections experiencing the MR lab

After the initial group of four students undergoes the MR module, the other group of four students is asked to engage in the MR module. This systematic procedure has been consistently implemented across all groups in all the sections, ensuring every student's active participation and facilitating the study's management and data collection. Subsequently, two weeks after experiencing the MR module, all students are requested to retake the PSVT:R test and complete the self-reflection surveys. All 102 students took the PSVT:R test during the lecture; however, only 90 completed the self-reflection survey.

The collected data comprised 102 responses for the PSVT:R test and 90 responses for the self-reflection surveys. The data collection process was administered through BrightSpace, an online course management platform. Following the completion of surveys on BrightSpace, unique identifiers were assigned, ensuring the removal of students' names from the data, thereby maintaining the confidentiality of time-series data.

5. Study Findings

After conducting the experiments and collecting the data, the students' grades on the Revised PSVT: R before and after the MR lab are analyzed using charts, scatter diagrams, and other visual representations. Also, the students' responses to the self-reflection surveys (Semantic differential and Likert scale questions) are examined using descriptive statistical methods, i.e., mean and standard deviation computations. The Revised PSVT: R and survey results are reported in the following subsections.

5.1. PSVT:R Results (102 Response)

The Revised PSVT:R results show that the class average on the Revised PSVT:R before conducting the MR lab was around 74%. Following the MR lab experience, there was an adequate increase, with the class average rising to 80%. This slight increase in the class average from 74% to 80% proves the positive impact of the MR lab on students' spatial abilities. It reveals that exposing students to more MR labs for longer times has the potential to enhance their spatial skills.

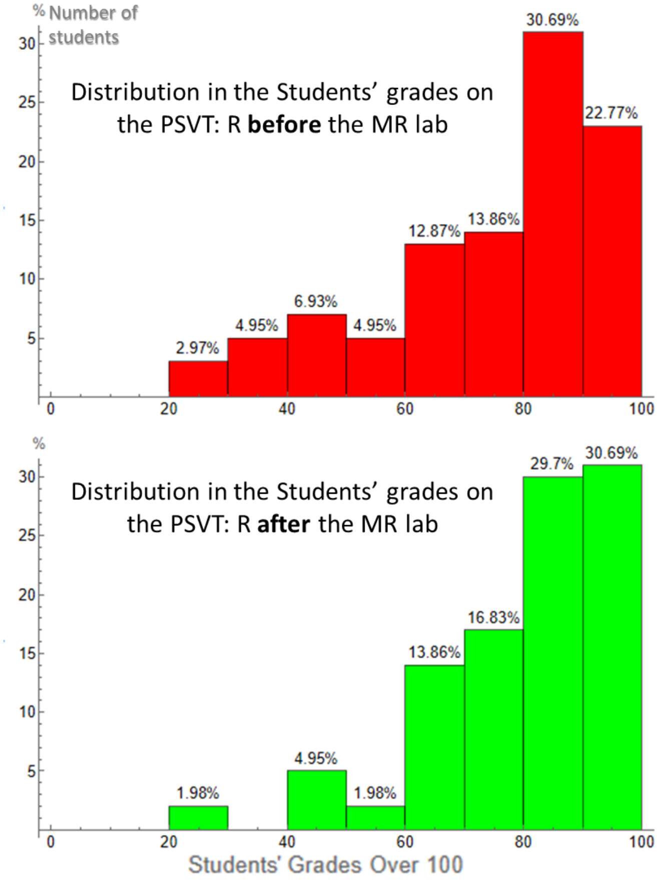


Figure 7. Comparing the distributions in students' grades pre-and-post the MR lab

For a better understanding of the PSVT:R results, Figure 7 presents a graphical representation for comparison of the grade distribution among the 102 students before and after the MR module. The analysis reveals that approximately 53% of students scored between 80 and 100 on the Revised PSVT:R test before the MR lab. Following their exposure to the MR lab, this percentage increased to 61%, indicating the potential of MR technology to improve the students' spatial abilities. Conversely, prior to the MR lab, around 20% of students received grades below 60, and this percentage significantly decreased to 8% after students engaged with the MR module. These observations emphasize the MR lab's positive impact on students' performance, contributing to future efforts in utilizing advanced technologies for addressing spatial visualization problems.

5.2. Self-Reflection Data Results (90 Response)

As mentioned previously, 90 of 102 students completed the self-reflection surveys. The results of the descriptive analysis of the students' responses are discussed in the following subsections.

5.2.1. Likert-Scale Data

The descriptive analysis outcomes of the students' responses to the first three Likert scale questions related to spatial abilities are reported in Table 2 and Figure 8. Table 2 reveals that Q1, Q2, and Q3 got high mean values (above 4) and low standard deviations (below 0.5), with Q2 receiving the highest mean value ***(M = 4.31, SD = 0.40),*** followed by Q1 ***(M = 4.12, SD = 0.38),*** and then Q3 ***(M = 4.08, SD = 0.39)***. These significant results indicate that most of the students' responses to the three questions (more than 80%) ranged between "Agree" and "Strongly Agree". Students reported their ability to perceptually visualize the gripper designs' internal structure, confirming MR’s impact in enhancing their spatial reasoning. This also emphasizes the effectiveness of MR features in providing students with a visceral experience where they can visualize and interact with virtual assets as if they are tangibly presented.

Table 2. M and SD for self-reflection Likert scale questions (spatial abilities and visualization)

Spatial Ability-Related Questions	***Minimum “Strongly Disagree”***	***Maximum “Strongly Agree”***	***M (Mean)***	***SD (Standard Deviation)***
Q1	1	5	4.12	0.38
Q2	1	5	4.31	0.40
Q3	1	5	4.08	0.39

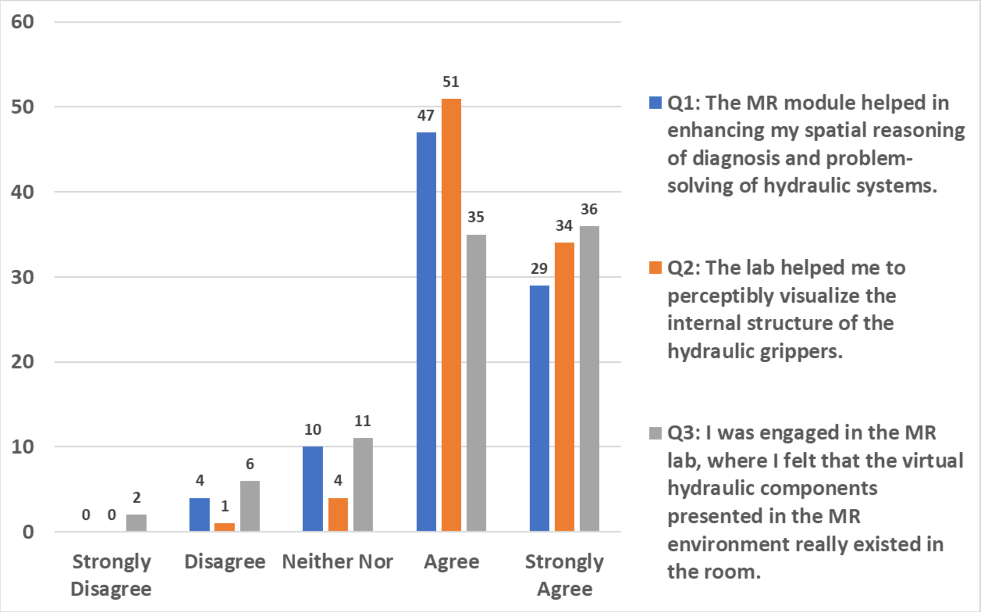


Figure 8. Students’ responses to the spatial ability-related Likert scale questions

These results are supported in Figure 8. For instance, the results of Q2, which got the highest mean value, show that 85 out of the 90 responses (94%) were “Agree” and “Strongly Agree”, 4% were “Neither Nor”, and the rest (2%) were “Disagree”, indicating that the majority of the students (94%) were able to visualize the gripper components and mechanisms. The results of Q1, shown in the blue bars, reveal that 84% of the students’ responses ranged from “Agree” to “Strongly Agree”, 11% were “Neither Nor”, and the rest 5% were “Disagree”. A very minimal percentage (below 6%) reported “Disagree” in Q1 and Q2, and nobody reported “Strongly Disagree”, which reveals that the students had positive attitudes toward utilizing MR for spatial visualization and learning. Besides Q1 and Q2, the results of Q3 are also relatively positive (78% for “Agree” and “Strongly Agree”, 12% for “Neither Nor”, 7% for “Disagree”, and 3% for “Strongly Disagree”), but not as significant as the results of Q1 and Q2. This shows that while students could visualize the virtual components as realistic in the MR setting, the entire module did not feel practical, given the lack of tactile experience. Therefore, this calls for refining the module by incorporating advanced haptic feedback into MR technology to enhance the students’ overall experience.

The descriptive analysis results of the students' responses to the Likert scale questions (Q4 to Q7) related to engineering learning are reported in Table 3 and Figure 9. Table 3 shows that Q5 and Q7 got mean values above 4, ***(M = 4.33, SD = 0.41)*** for Q5 and ***(M = 4.04, SD = 0.41)*** for Q7, indicating that the MR lab helped the students reflect on their understanding of engineering concepts, like design, system analysis, testing, and mechanism operation. These results are supported in Figure 9, in the orange and yellow bars. As shown in the figure, 50% of the students' responses to Q5 were "Strongly Agree", 37% were "Agree", 10% were "Neither Nor", and the rest (3%) were "Disagree", where nobody reported "Strongly Disagree". Similarly, for Q7, 82% was divided between "Agree" (53%) and "Strongly Agree" (29%), 16% for "Neither Nor" and the rest (2%) were equally divided between "Disagree" and "Strongly Disagree".

Table 3. M and SD for self-reflection Likert scale questions (engineering learning)

Engineering Learning-Related Questions	***Minimum "Strongly Disagree"***	***Maximum "Strongly Agree"***	***M (Mean)***	***SD (Standard Deviation)***
Q4	1	5	3.9	0.36
Q5	1	5	4.33	0.41
Q6	1	5	3.98	0.37
Q7	1	5	4.08	0.38

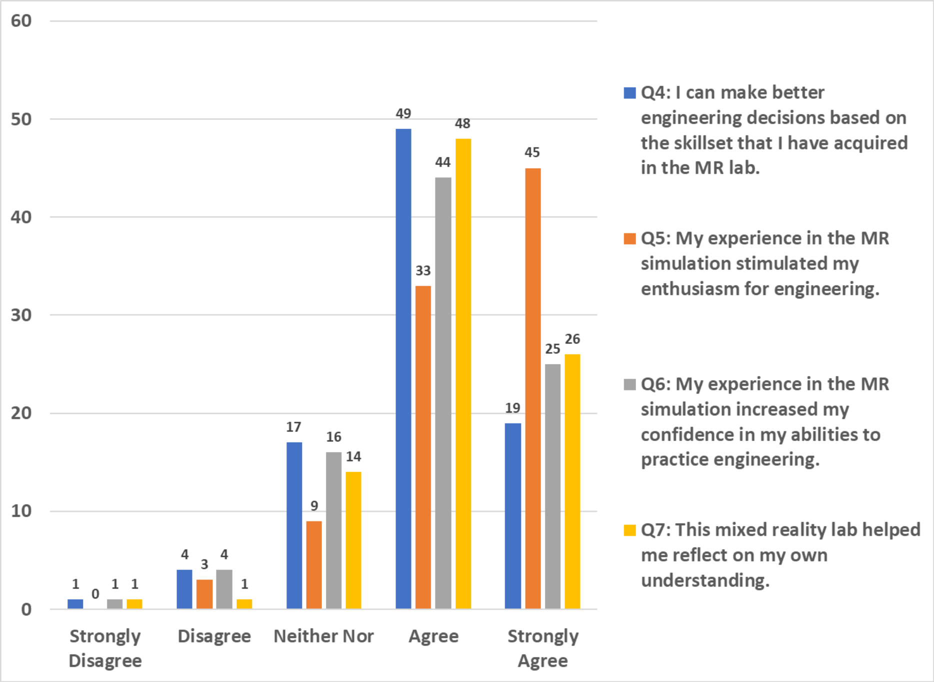


Figure 9. Students' responses to the engineering-related Likert scale questions

Besides Q5 and Q7, the other questions Q4 and Q6 exhibit very close results, ***(M = 3.9, SD = 0.36)*** for Q4 and ***(M = 3.98, SD = 0.37)*** for Q6. This reveals that most students (more than 75%) had positive feedback regarding their confidence in their engineering design abilities after conducting the MR lab (see Figure 9). The MR lab allowed enhancing technology students' engineering design skills, reinforcing their confidence in their abilities.

5.2.2. Semantic Differential Data

The statistical analysis results of the semantic differential questions (Q8, Q9, and Q10) are reported in Table 4 and Figure 10. Table 4 shows that the three questions got high mean values (above 4) and low standard deviations (below 0.4), with Q10 receiving the highest mean ***(M = 4.52, SD = 0.43)***, followed by Q9 ***(M = 4.46, SD = 0.42)***, and then Q8 ***(M = 4.33, SD = 0.41).*** These results are supported in Figure 10. The diagram in the figure shows that up to 96% of the students' responses to Q10 were positive, divided between "Likely" (38%) and "Very Likely" (58%), as highlighted in the grey bars. Also, the responses to Q9 were positive, where up to 92% of the students responded as "Likely" and "Very Likely", with a minimal percentage (below 1%) reporting negative feedback. Similarly, the results of Q8 are promising; up to 94% of the students' responses ranged between "Likely" and "Very Likely", with a small percentage of around 3% "Unlikely". These results reflect the students' interest in involving MR in their fluid power laboratories. They demonstrate the benefits of employing advanced digital reality technologies, like MR, on students' learning experience and engagement.

Table 4. M and SD for self-reflection semantic differential questions

Questions	***Minimum "Very Uncertain"***	***Maximum "Very Likely"***	***M (Mean)***	***SD (Standard Deviation)***
Q8	1	5	4.33	0.41
Q9	1	5	4.46	0.42
Q10	1	5	4.52	0.43

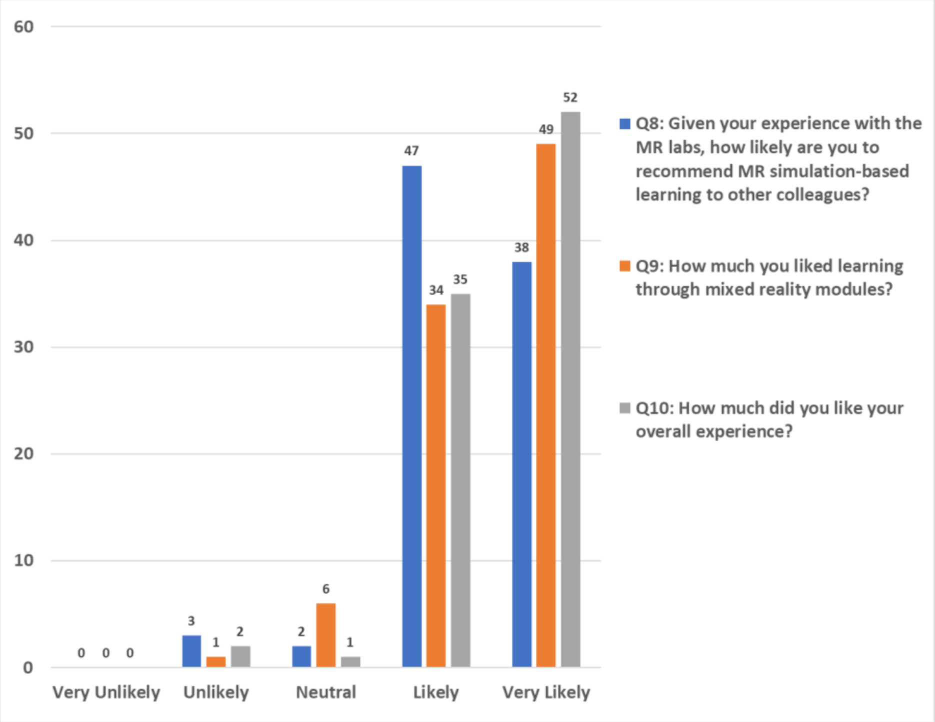


Figure 10. Data collected from the students' responses to semantic differential questions

6. Conclusions and Future Work

The contribution behind this work relies on exploring MR technology as a teaching tool for improving students' cognitive spatial thinking and thus reinforcing their technical engineering skills, e.g., diagnosis and simulation, problem-solving, and comprehensive perception. Throughout this work, an interactive MR module on hydraulic grippers' design and operation has been developed using MR functionalities to be incorporated into Fluid Power courses. A research study has been conducted at the Fluid Power course to examine the effect of MR on the students' spatial skills and engineering learning outcomes. The MR module, comprising a 10-minute tutorial session and 20-minute simulation lab, was experienced by 102 students enrolled in the course. The Revised PSVT: R assessment tool designed and provided by Purdue University was used to assess the improvement in students' spatial skills. Also, self-reflection surveys consisting of Likert scale and semantic differential questions have been designed and completed by 90 students to examine the improvement in their understanding and test their attitudes toward the MR technology. The study findings demonstrated the positive effect of MR technology on enhancing students' spatial abilities, as the class average on the PSVT: R test increased from 74% (before MR lab) to 80%. (after MR lab). This slight improvement could be further enhanced by exposing students to additional MR labs, allowing them to visualize more complex 3D shapes in MR settings. Moreover, the results revealed the favorable influence of MR on students' overall learning experience, with over 94% of students expressing interest in learning through MR modules.

Our research team is currently focused on designing and implementing shared MR environments to enhance student collaborative experiences. The team intends to enhance the MR experience by transitioning it from a single-user to a multi-user interface with the goal of reinforcing students' experiences. Our team achieved the first milestone in shared MR settings, and we are looking forward to testing the MR shared setting in future endeavors through a secondary research study.

References

[1] J. H. Mathewson, "Visual-Spatial Thinking: An Aspect of Science Overlooked by Educators," *Sci. Educ.*, vol. 83, no. 1, pp. 1098–237, 1999, doi: 10.1002/(SICI)1098-237X(199901)83:1.

[2] R. Lloyd, "A Historical Review of Visualization in Human Cognition," vol. 43, no. 1, pp. 45–56, 1995.

[3] G. Duffy, S. Sorby, and B. Bowe, "An investigation of the role of spatial ability in representing and solving word problems among engineering students," *J. Eng. Educ.*, vol. 109, no. 3, pp. 424–442, Jul. 2020, doi: 10.1002/JEE.20349.

[4] M. Kozhevnikov, M. A. Motes, and M. Hegarty, "Spatial Visualization in Physics Problem Solving," *Cogn. Sci.*, vol. 31, no. 4, pp. 549–579, Jul. 2007, doi: 10.1080/15326900701399897.

[5] D. Bairaktarova, M. Reyes, N. Nassr, and D. T. Carlton, "Spatial skills development of engineering students: Identifying instructional tools to incorporate into existing curricula.," in *2015 ASEE Annual Conference & Exposition*, 2015, pp. 26–1389.

[6] R. M. Onyancha, M. Derov, and B. L. Kinsey, "Improvements in Spatial Ability as a Result of Targeted Training and Computer-Aided Design Software Use: Analyses of Object Geometries and Rotation Types," *J. Eng. Educ.*, vol. 98, no. 2, pp. 157–167, Apr. 2009, doi: 10.1002/J.2168-9830.2009.TB01014.X.

[7] S. Strong and R. Smith, "Spatial Visualization: Fundamentals and Trends in Engineering Graphics CAD Design Graphic Communications Visual Communications Teaching Methods Spatial Visualization: Fundamentals and Trends in Engineering Graphics," *J. Ind. Technol.* , vol. 18, no. 1, 2001, Accessed: Jan. 15, 2024. [Online]. Available: www.nait.org

[8] S. Tumkor and R. Harm de Vries, "Enhancing spatial visualization skills in engineering drawing courses.," in *In 2015 ASEE annual conference & exposition,* 2015, pp. 26–663.

[9] C. Charcharos, M. Kokla, and E. Tomai, "Investigating the Influence of Spatial Thinking in Problem Solving," in *In 19th AGILE International Conference on Geographic Information Science.,* 2016, pp. 1–5. doi: 10.13140/RG.2.1.4186.0729.

[10] D. Van Garderen, "Spatial Visualization, Visual Imagery, and Mathematical Problem Solving of Students With Varying Abilities," *J. Learn. Disabil.* , vol. 39, no. 6, pp. 496–506, Nov. 2006, doi: 10.1177/00222194060390060201.

[11] Y. S. Allam, "Enhancing spatial visualization skills in first-year engineering students," Ohio State University , 2010.

[12] C. Brus, L. Zhao, and J. Jessop, "Visual-spatial ability in first-year engineering students: A useful retention variable?," in *2004 ASEE Annual Conference Proceedings,* 2004, pp. 15361–15373. doi: 10.18260/1-2--13248.

[13] T. Lowrie, T. Logan, and M. Hegarty, "The Influence of Spatial Visualization Training on Students' Spatial Reasoning and Mathematics Performance," *J. Cogn. Dev.*, vol. 20, no. 5, pp. 729–751, Oct. 2019, doi: 10.1080/15248372.2019.1653298.

[14] D. L. Shea, D. Lubinski, and C. P. Benbow, "Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study," *J. Educ. Psychol.*, vol. 93, no. 3, pp. 604–614, 2001, doi: 10.1037/0022-0663.93.3.604.

[15] S. Titus and E. Horsman, "Characterizing and Improving Spatial Visualization Skills," *J. Geosci. Educ.*, vol. 57, no. 4, pp. 242–254, 2009, doi: 10.5408/1.3559671.

[16] C. Roca-González, J. Martin-Gutierrez, M. García-Dominguez, and M. del C. M. Carrodeguas, "Virtual technologies to develop visual-spatial ability in engineering students," *Eurasia J. Math. Sci. Technol. Educ.*, vol. 13, no. 2, pp. 441–468, 2017, doi: 10.12973/EURASIA.2017.00625A.

[17] J. Kim and J. Irizarry, "Evaluating the Use of Augmented Reality Technology to Improve Construction Management Student's Spatial Skills," *Int. J. Constr. Educ. Res.*, vol. 17, no. 2, pp. 99–116, Apr. 2021, doi: 10.1080/15578771.2020.1717680.

[18] C. M. Pedrosa, B. R. Barbero, and A. R. Miguel, "Spatial Visualization Learning in Engineering: Traditional Methods vs. a Web-Based Tool," *Educ. Technol. Soc.*, vol. 17, no. 2, pp. 142–157, 2014.

[19] C. M. Pedrosa, R. Barbero, M. Esther, B. Ban˜, B. Garci´a, and G. Garci´a, “Interactive learning management system to develop spatial visualization abilities,” *Comput. Appl. Eng. Educ.*, vol. 23, no. 2, pp. 203–216, Mar. 2015, doi: 10.1002/CAE.21590.

[20] “Universidad Nacional Autónoma de México Facultad de Ciencias Políticas y Sociales.”

[21] H. Borges de Barros Pereira, “Análisis experimental de los criterios de evaluación de usabilidad de aplicaciones multimedia en entornos de educación y formación a distancia,” *TDX (Tesis Dr. en Xarxa)*, Jul. 2002, doi: 10.5821/DISSERTATION-2117-93853.

[22] X. Xiang and Y. Liu, “Exploring and enhancing spatial thinking skills: Learning differences of university students within a web-based GIS mapping environment,” *Br. J. Educ. Technol.*, vol. 50, no. 4, pp. 1865–1881, Jul. 2019, doi: 10.1111/BJET.12677.

[23] A. Saeed Alqahtani, L. Foaud Daghestani, and L. Fattouh Ibrahim, “Techniques used to Improve Spatial Visualization Skills of Students in Engineering Graphics Course: A Survey,” *Int. J. Adv. Comput. Sci. Appl.*, vol. 8, no. 3, 2017, Accessed: Jan. 15, 2024. [Online]. Available: www.ijacsa.thesai.org

[24] M. Contero, F. Naya, P. Company, J. L. Saorín, and J. Conesa, “Improving visualization skills in engineering education,” *IEEE Comput. Graph. Appl.*, vol. 25, no. 5, pp. 24–31, Sep. 2005, doi: 10.1109/MCG.2005.107.

[25] R. V. Fleisig, A. Robertson, and A. D. Spence, “IMPROVING THE SPATIAL VISUALIZATION SKILLS OF FIRST YEAR ENGINEERING STUDENTS,” in *Proceedings of the Canadian Engineering Education Association (CEEA)*, Aug. 2011, vol. 0, no. 0. doi: 10.24908/pceea.v0i0.4050.

[26] K. Holliday, -Darr Penn, S.-E. Dawn, and G. Blasko, “Improve Cognitive Visualization with a Web Based Interactive Assessment and Training Program,” *Eng. Des. Graph. J.*, vol. 64, no. 1, 2000, Accessed: Jan. 15, 2024. [Online]. Available: http://edgj.org/index.php/EDGJ/article/view/137

[27] C. S. Park, Q. T. Le, A. Pedro, and C. R. Lim, “Interactive Building Anatomy Modeling for Experiential Building Construction Education,” *J. Prof. Issues Eng. Educ. Pract.*, vol. 142, no. 3, p. 04015019, Jul. 2016, doi: 10.1061/(ASCE)EI.1943-5541.0000268/ASSET/134AFDC1-CFBB-4173-922B-6A8D690D61BD/ASSETS/IMAGES/LARGE/FIGURE10.JPG.

[28] M.-B. Ibáñez and C. Delgado-Kloos, “Augmented reality for STEM learning: A systematic review,” *Comput. Educ.*, vol. 123, pp. 109–123, Aug. 2018, doi: 10.1016/J.COMPEDU.2018.05.002.

[29] I. Azzam, P. Soudah, and F. Breidi, “Virtual Reality: A Learning Tool for Promoting Learners’ Engagement in Engineering Technology,” in *THE 2023 ASEE ANNUAL CONFERENCE AND EXPOSITION. Baltimore Convention Center MD*, 2023. [Online]. Available: https://peer.asee.org/virtual-reality-a-learning-tool-for-promoting-learners-engagement-in-engineering-technology

[30] I. Azzam, F. Breidi, M. Akedre, and C. Mousas, “DESIGN VALIDATION OF A MECHANICALLY ACTUATED DIGITAL PUMP USING MIXED REALITY

TECHNOLOGY," in *The 18th Scandinavian International Conference on Fluid Power, SICFP23,* 2023.

[31] L. Stewart and C. Lopez, "Developing Spatial Visualization Skills with Virtual Reality and Hand Tracking," *Commun. Comput. Inf. Sci.*, vol. 1498 CCIS, pp. 390–398, 2021, doi: 10.1007/978-3-030-90176-9_51/FIGURES/8.

[32] P. Safadel and D. White, "Effectiveness of Computer-Generated Virtual Reality (VR) in Learning and Teaching Environments with Spatial Frameworks," *Appl. Sci.* , vol. 10, no. 16, p. 5438, Aug. 2020, doi: 10.3390/APP10165438.

[33] G. Ardito and G. Ardito, "Patterns of Interactions During the Learning of Computer Science and...," in *Society for Information Technology & Teacher Education International Conference,* 2021, vol. 2021, no. 1, pp. 1146–1154. Accessed: Jan. 15, 2024. [Online]. Available: https://www.learntechlib.org/primary/f/219321/

[34] P. Katsioloudis, M. Jones, and V. Jovanovic, "Use of Virtual Reality head-mounted displays for Engineering Technology Students and Implications on Spatial Visualization ability as measured through rotational view drawings.," *Eng. Des. Graph. J.*, vol. 81, no. 1, 2017, Accessed: Jan. 15, 2024. [Online]. Available: http://www.edgj.org/index.php/EDGJ/article/view/546

[35] T. J. Barrett and M. Hegarty, "Effects of interface and spatial ability on manipulation of virtual models in a STEM domain," *Comput. Human Behav.*, vol. 65, pp. 220–231, Dec. 2016, doi: 10.1016/J.CHB.2016.06.026.

[36] F. Salehi, J. Mohammadpour, R. Abbassi, S. Cheng, S. Diasinos, and R. Eaton, "Developing an Interactive Digital Reality Module for Simulating Physical Laboratories in Fluid Mechanics," *Australas. J. Eng. Educ.*, vol. 27, no. 2, pp. 100–114, Jul. 2022, doi: 10.1080/22054952.2022.2162673.

[37] T. A. Mikropoulos and A. Natsis, "Educational virtual environments: A ten-year review of empirical research (1999–2009)," *Comput. Educ.*, vol. 56, no. 3, pp. 769–780, Apr. 2011, doi: 10.1016/J.COMPEDU.2010.10.020.

[38] Q. Zhao, "10 scientific problems in virtual reality," *Communications of the ACM*, vol. 54, no. 2, ACM PUB27 New York, NY, USA , pp. 116–118, Feb. 01, 2011. doi: 10.1145/1897816.1897847.

[39] M. Chen, Y. Jin, T. Goodall, X. Yu, and A. C. Bovik, "Study of 3D Virtual Reality Picture Quality," *IEEE J. Sel. Top. Signal Process.*, 2019, doi: 10.1109/JSTSP.2019.2956408.

[40] E. Chang, H. Taek Kim, and B. Yoo, "Virtual Reality Sickness: A Review of Causes and Measurements," *Int. J. Hum. Comput. Interact.*, vol. 36, no. 17, pp. 1658–1682, 2020, doi: 10.1080/10447318.2020.1778351.

[41] K. M. Stanney, R. S. Kennedy, J. M. Drexler, and D. L. Harm, "Motion sickness and proprioceptive aftereffects following virtual environment exposure," *Appl. Ergon.*, vol. 30, no. 1, pp. 27–38, Feb. 1999, doi: 10.1016/S0003-6870(98)00039-8.

[42] S. Palmisano and R. Constable, "Reductions in sickness with repeated exposure to HMD-based virtual reality appear to be game-specific," *Virtual Real.*, vol. 26, no. 4, pp. 1373–

1389, Dec. 2022, doi: 10.1007/S10055-022-00634-6/FIGURES/8.

[43] E. Chang, H. T. Kim, and B. Yoo, "Virtual Reality Sickness: A Review of Causes and Measurements," *Int. J. Hum. Comput. Interact.*, pp. 1658–1682, 2020, doi: 10.1080/10447318.2020.1778351.

[44] S. Yuen, G. Yaoyuneyong, and E. Johnson, "Augmented reality: An overview and five direc-tions for AR in education," *J. Educ. Technol. Dev. Exch.*, vol. 4, no. 1, pp. 119–140, 2011, doi: 10.18785/jetde.0401.10.

[45] J. Carmigniani and B. Furht, "Augmented Reality: An Overview," *Handb. Augment. Real.*, pp. 3–46, 2011, doi: 10.1007/978-1-4614-0064-6.

[46] M. Bi *et al.*, "Review of the Research on Augmented Reality Maintenance Assistant System of Mechanical System You may also like Application of Augmented Reality (AR) Technology in Low-Voltage Line Interruption Training and Power Grid Emergency Training Review of the Research on Augmented Reality Maintenance Assistant System of Mechanical System," *J. Phys. Conf. Ser.*, vol. 1748, p. 62041, 2021, doi: 10.1088/1742-6596/1748/6/062041.

[47] P. Salinas, E. González-Mendívil, E. Quintero, H. Ríos, H. Ramírez, and S. Morales, "The Development of a Didactic Prototype for the Learning of Mathematics through Augmented Reality," *Procedia Comput. Sci.*, vol. 25, pp. 62–70, Jan. 2013, doi: 10.1016/J.PROCS.2013.11.008.

[48] E. Quintero, P. Salinas, E. González-Mendívil, and H. Ramírez, "Augmented Reality app for Calculus: A Proposal for the Development of Spatial Visualization," *Procedia Comput. Sci.*, vol. 75, pp. 301–305, Jan. 2015, doi: 10.1016/J.PROCS.2015.12.251.

[49] A. Dünser, K. Steinbügl, H. Kaufmann, and J. Glück, "Virtual and augmented reality as spatial ability training tools," *ACM Int. Conf. Proceeding Ser.*, vol. 158, pp. 125–132, 2006, doi: 10.1145/1152760.1152776.

[50] M. Ikhsan, S. Guntur, and W. Setyaningrum, "The Effectiveness of Augmented Reality in Learning Vector to Improve Students' Spatial and Problem-Solving Skills," *Int. J. Interact. Mob. Technol.*, vol. 15, no. 5, 2021, doi: 10.3991/ijim.v15i05.19037.

[51] P. Christos, T. Christos, K. Akrivi, and S. Cleo, "Exploration of Augmented Reality in Spatial Abilities Training: A Systematic Literature Review for the Last Decade," *Informatics Educ. - An Int. J.*, vol. 20, no. 1, pp. 107–130, 2021.

[52] M. J. Liberatore and W. P. Wagner, "Virtual, mixed, and augmented reality: a systematic review for immersive systems research," *Virtual Real. 2021 253*, vol. 25, no. 3, pp. 773–799, Jan. 2021, doi: 10.1007/S10055-020-00492-0.

[53] S. Rokhsaritalemi, A. Sadeghi-Niaraki, and S. M. Choi, "A Review on Mixed Reality: Current Trends, Challenges and Prospects," *Appl. Sci.*, vol. 10, no. 2, p. 636, Jan. 2020, doi: 10.3390/APP10020636.

[54] M. Speicher, B. D. Hall, and M. Nebeling, "What is mixed reality?," in *Conference on Human Factors in Computing Systems - Proceedings*, May 2019, vol. 15. doi: 10.1145/3290605.3300767.

[55] "Spatial mapping - Mixed Reality," *Microsoft Learn*, Jan. 31, 2023. https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-mapping (accessed Jan. 16, 2024).

[56] "Spatial awareness getting started - MRTK 2," *Microsoft Learn*, Aug. 01, 2022. https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/features/spatial-awareness/spatial-awareness-getting-started?view=mrtkunity-2022-05 (accessed Jan. 16, 2024).

[57] "Spatial anchors - Mixed Reality," *Microsoft Learn*, Mar. 02, 2023. https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-anchors (accessed Jan. 16, 2024).

[58] "Eye tracking overview - Mixed Reality," *Microsoft Learn*, Mar. 02, 2023. https://learn.microsoft.com/en-us/windows/mixed-reality/design/eye-tracking#head-and-eye-tracking-design-concepts-demo (accessed Jan. 17, 2024).

[59] "Magic Leap 2 | The most immersive enterprise AR device," *Magic Leap*. https://www.magicleap.com/en-us/ (accessed Jan. 16, 2024).

[60] "HoloLens 2—Overview, Features, and Specs ," *Microsoft HoloLens*. https://www.microsoft.com/en-us/hololens/hardware#document-experiences (accessed Jan. 16, 2024).

[61] B. Kress, W. C. Cummings Bernard Kress, W. J. Cummings, and B. C. Kress, "Optical architecture of HoloLens mixed reality headset," *Digit. Opt. Technol.*, vol. 10335, no. 26, pp. 124–133, Jun. 2017, doi: 10.1117/12.2270017.

[62] I. Azzam *et al.*, "Design Validation of a Mechanically Actuated Digital Pump Using Mixed Reality Technology.," in *Scandinavian International Conference on Fluid Power (SICFP) Tampere, Finland*, 2023.

[63] I. Azzam, K. Pate, and F. Breidi, "MIXED REALITY TECHNOLOGY: A VIRTUAL TRAINING TOOL IN FLUID POWER ENGINEERING," in *2023 ASME/BATH Symposium on Fluid Power and Motion Control*, 2023.

[64] Y. Jiang, M. Akdere, M. soo Choi, I. Azzam, F. El Breidi, and C. Mousas, "An investigation of the effects of mixed reality on increasing STEM students' career interests in technology on Education in Mathematics, Science and Technology (ICEMST).," in *Nevsehir: Refereed Abstract Book of the International Conference*, 2023, p. 53.

[65] M. Akdere, Y. Jiang, M. soo Choi, I. Azzam, F. El Breidi, and C. Mousas, "Promoting team collaboration in engineering teams through mixed reality technology.," in *The Proceedings Book of the International Engineering and Technology Management Summit.*, 2022.

[66] I. Azzam, K. Pate, F. Breidi, M. Choi, Y. Jiang, and C. Mousas, "Mixed Reality: A Tool for Investigating the Complex Design and Mechanisms of a Mechanically Actuated Digital Pump," *Actuators* , vol. 12, no. 11, p. 419, Nov. 2023, doi: 10.3390/ACT12110419.

[67] S. Y. Yoon, "Psychometric properties of the revised Purdue Spatial Visualization Tests:

Visualization of Rotations (THE Revised PSVT:R)," Purdue University, 2011. Accessed: Jan. 17, 2024. [Online]. Available: http://www.purdue.edu/policies/pages/teach_res_outreach/c_22.html

[68] "Unity Real-Time Development Platform | 3D, 2D, VR & AR Engine." https://unity.com/ (accessed Apr. 23, 2023).

[69] "MRTK2-Unity Developer Documentation - MRTK 2 | Microsoft Learn," *Microsoft Ignite*, 2022. https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05 (accessed Oct. 03, 2022).

[70] "Welcome to the Mixed Reality Feature Tool - Mixed Reality," *Microsoft Learn*. https://learn.microsoft.com/en-us/windows/mixed-reality/develop/unity/welcome-to-mr-feature-tool (accessed Apr. 23, 2023).

[71] S. Y. Yoon and E. L. Mann, "Exploring the Spatial Ability of Undergraduate Students: Association With Gender, STEM Majors, and Gifted Program Membership," *Gift. Child Q.*, vol. 61, no. 4, pp. 313–327, Oct. 2017, doi: 10.1177/0016986217722614/ASSET/IMAGES/LARGE/10.1177_0016986217722614-FIG2.JPEG.