Analysis of User Experience in Digital Reality: A Comparative Study of VR and MR for Manufacturing Training

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Analysis of User Experience in Extended Reality: A Comparative Study of VR and MR for Manufacturing Training

Abstract

With the rise of Industry 4.0, extended reality (XR) technologies, including Virtual Reality (VR) and Mixed Reality (MR), have become integral to manufacturing training and education. This enables the simulation of real-world scenarios in controlled, safe environments to address competition in the manufacturing sector. Both VR and MR technologies have shown the potential to reduce training costs by eliminating the need for physical equipment and mitigating safety risks. However, VR and MR environments present challenges related to user experience (UX), interaction, environmental functionality, and hardware/software limitations, which can impact overall performance in manufacturing training contexts. Therefore, this work explores the distinct features, capabilities, and limitations of VR and MR environments from users' perspectives during manufacturing assembly tasks to identify the best XR environment that improves UX. A research study involving 95 undergraduate engineering students was conducted, where VR and MR settings were designed with interactive manufacturing training modules. Various sensory modalities, including auditory and visual elements, were incorporated to evaluate UX. Quantitative and qualitative assessment tools were employed to measure participants' attitudes. The quantitative data was analyzed using statistical methods, while the qualitative data was processed through Natural Language Processing (NLP) techniques, specifically the Latent Dirichlet Allocation (LDA) topic model. The results showed that the MR environment is more effective for manufacturing training than VR, offering an immersive and interactive experience. Users reported that MR settings reduced discomfort and safety risks, as its holographic features enable real-time interaction with the physical environment while maintaining spatial awareness.

Keywords: Virtual Reality, Mixed Reality, Manufacturing Training, User Experience, Natural Language Processing

1. Introduction

The manufacturing sector is the cornerstone of the U.S. economy, driving industrial development for more than 200 years [1]. The fourth industrial revolution, aka Industry 4.0, has revolutionized manufacturing processes by integrating digital and smart technologies, transforming traditional practices into what is now known as smart or advanced manufacturing [2]. The adoption of advanced technologies such as the Industrial Internet of Things (IIoT), artificial intelligence (AI), cloud computing, and extended reality (XR) have significantly improved manufacturing processes by reducing costs, minimizing production time, and enhancing operator efficiency [3]. Thus, it has become essential to maintain competitiveness in the face of rapid technological advancements and global competition [4]. This digital transformation in the manufacturing sector has enabled interconnected networks of machinery, sensors, and data analytics platforms, fostering real-time monitoring, predictive maintenance, and data-driven decision-making [5]. It provided manufacturers and human operators with highly advanced digital tools to maintain profitability in an increasingly globalized and digitalized marketplace.

Besides these benefits to industrial development and the U.S. economy, the transition to smart manufacturing processes has also introduced several challenges, particularly in workforce development. [6]. The complexity of smart manufacturing systems has created a substantial skillset gap, requiring expertise in areas such as data analytics, robotics, machine learning, and AI, skills that cannot be effectively developed through traditional manufacturing training [7]. This gap has significantly impacted labor recruitment, creating hurdles for employers and recruiters. For instance, the shortage of skilled workers has led to competition for top talent in the manufacturing industry. Employers are now competing not only within the sector but also with other industries for workers with digital skills and adaptability.

In response to this issue, around 57% of manufacturing firms have expanded their hiring criteria to include candidates with industry certifications and credentials, shifting away from strict degree requirements [8]. Further, recruiters have been collaborating with educational institutions and STEM-focused programs to target workers with strong technical backgrounds [9]. Despite these efforts, a recent study by the Manufacturing Institute reported that the manufacturing industry is still facing a severe labor shortage, with up to 3.8 million jobs potentially needing to be filled by 2033 [10]. If these workforce challenges remain unresolved, more than 1.9 million of these positions will go unfilled due to the growing disparity between the demand for skilled workers and the availability of qualified talent and skillset [11].

Addressing such challenges necessitates the training of a new category of professionals known as "technologists", individuals who combine theoretical engineering knowledge with practical, hands-on skills to meet the demands of the digital transformation in the manufacturing sector [12]. One approach is integrating smart digital technologies into manufacturing education in coordination with traditional teaching modules. This includes updating curricula to develop comprehensive training programs that incorporate automation, simulation-based courseware, XR, and other advanced tools. The integration of such advanced technologies into educational frameworks will expose future generations of the workforce to the critical systems and processes that define modern manufacturing. Students will get the opportunity to develop adaptability and problem-solving skills besides their technical proficiency, enabling them to work effectively with cutting-edge systems such as robotics, IoT, and AI-driven platforms.

Amidst many digital technologies, immersive XR systems, from virtual reality (VR) to augmented reality (AR) and mixed reality (MR), have emerged as training and educational tools for manufacturing training campaigns [13]–[15]. XR systems offer unique advantages for manufacturing training, such as simulating high-risk environments and providing interactive training modules [16]–[18]. However, these systems also present challenges related to user experience (UX), including motion sickness, user adaptability to virtual interfaces and controls, network synchronization, and hardware limitations [19]–[21]. Such issues can overwhelm users, impacting the effectiveness of training, particularly in collaborative and multi-user environments [22], thereby limiting seamless collaboration and overall training outcomes. The UX challenges can significantly affect manufacturing training outcomes. Motion sickness or discomfort can shorten training sessions, steep learning curves can detract users from the content, and hardware limitations might also restrict participation. Given these limitations, this study is motivated by the need to further investigate the functionalities of XR environments from a UX perspective for manufacturing training. It aims to explore the distinct features, capabilities, and limitations of each environment during manufacturing assembly tasks to identify the optimal setting for a comfortable and effective UX. The study will answer the following research questions:

RQ1: Does UX impact students' learning in advanced VR/MR manufacturing training environments?
RQ2: Which XR environment, VR or MR, is most effective for manufacturing training?

To answer these questions, a research study is conducted, where VR and MR manufacturing training modules are developed, incorporating sensory modalities such as auditory and visual elements. The training environments are then tested with a group of undergraduate engineering technology students. Quantitative and qualitative tools are employed to evaluate UX, with statistical methods applied to quantitative data and Natural Language Processing (NLP) techniques, e.g., Latent Dirichlet Allocation (LDA), used for qualitative analysis.

The rest of this paper is organized as follows. Section 2 provides an overview and background on the use of XR technologies for advanced manufacturing education and training, highlighting the benefits of XR and its limitations and challenges. Section 3 introduces the proposed manufacturing training module and discusses the development of the VR and MR environments, including system design, hardware/software setup, and integration into undergraduate courses for testing and evaluation. Section 4 outlines the research study, from the design of assessment tools to the adopted experimental framework and the data analysis methodologies. Section 5 presents the analysis of the collected data and associated results. Section 6 discusses the findings, leading to the selection of the best XR environment. Finally, Section 7 summarizes the key outcomes and contributions.

2. XR Environments for Advanced Manufacturing Training

As technology continues to advance rapidly, XR environments are increasingly utilized in manufacturing education to enhance learners' performance and expose them to the latest developments in smart manufacturing. The following subsections provide an overview of XR technologies, highlighting their benefits and limitations within the context of manufacturing training.

2.1. Benefits and Features of XR Systems

VR technology provides a fully immersive experience for users in a completely simulated virtual environment. VR enables the creation of realistic scenarios for safety training and practice, making it highly effective for simulating high-risk manufacturing environments and exposing trainees to complex, challenging situations [23], [24]. Replicating real-world manufacturing processes enables students to build critical skills and gain practical experience without the constraints and/or risks of traditional training methods.

Unlike VR, which immerses users in a fully virtual environment, **AR** overlays digital content onto the physical world through smart devices such as smartphones and tablets. In manufacturing education, AR enhances the learning process by providing interactive, real-time contextual information and imagery that guides students through tasks like equipment maintenance and assembly procedures [25], [26]. Thus, AR helps to bridge the gap between theoretical knowledge and hands-on application by allowing learners to visualize step-by-step instructions or access supplementary without leaving their physical environment, such as during lectures and laboratory sessions.

MR technology further expands on these capabilities by combining the immersive functionalities of VR with the contextual integration of AR, allowing virtual objects to be imposed on the physical world with advanced spatial recognition [27]. MR creates an integrated experience where physical and virtual elements coexist and interact seamlessly, making it useful in manufacturing training and collaborative applications [28], [29]. For example, students can practice operating machinery, visualizing workflows, or troubleshooting processes in real-time while working with both virtual and physical elements simultaneously. **One advanced form of MR** is holographic MR, which uses holograms, i.e., 3D digital representations of objects or information, to augment the user's perception of the real world [30]. This experience is achieved through holographic headsets like the Magic Leap [31] and Microsoft HoloLens [32], which enables holographic MR experiences by projecting virtual content directly into the user's field of view. This technology is valuable for teaching complex manufacturing tasks such as assembly procedures, design validation, and collaborative production planning. It allows educators to provide their learners with advanced training environments that mirror the complexities of modern manufacturing, preparing them for future industry-specific roles.

Therefore, the features of both VR and MR offer significant advantages over AR, particularly for manufacturing training. Both technologies provide a higher level of immersion compared to AR, which has been proven to enhance information retention and skill acquisition [33]. Additionally, VR and MR enable the safe simulation of potentially dangerous or complex scenarios, offering a more controlled training environment while avoiding real-world risks, i.e., situations that are impossible to recreate physically [34], [35]. Moreover, while AR applications often require users to hold devices like smartphones or tablets, VR and MR typically use head-mounted displays, enabling a hands-free, fully immersive experience. This hands-free functionality allows users to interact more naturally with the environment and facilitates seamless integration between the virtual and physical systems, particularly in collaborative training settings [21].

2.2. UX Challenges in VR and MR Systems

While immersive VR and MR offer significant potential for manufacturing training, they also present unique challenges, particularly from a UX perspective. Research studies reveal that VR applications, while offering higher levels of immersion than holographic MR, can cause discomfort or nausea, i.e., motion sickness, when used for extended periods, often after just 10 minutes of continuous exposure [19], [20], [36]. This physiological reaction limits the duration and effectiveness of training sessions, creating barriers to sustained engagement and learning. Additionally, the adaptability of users to virtual interfaces and user-interface (UI) controls varies between VR and MR applications, depending on the specific training module and context. In VR environments, the lack of physical reference (awareness of the surrounding world) leads to challenges in navigation and interaction, as users must rely entirely on virtual points [37]–[39] This limitation triggers the user's confusion and frustration, particularly for tasks requiring spatial awareness [40]. Holographic MR, while offering a more intuitive experience by blending

real and virtual elements, also presents usability challenges such as limited depth perception, constrained field of view (FOV), and difficulty manipulating virtual objects in 3D space [41], [42].
Besides motion sickness and adaptability, the complexity of the settings in both environments can overwhelm users, potentially leading to cognitive overload [43], [44]. Experiencing cognitive load can negatively impact learning retention and task performance, which are crucial in manufacturing contexts where precision and adherence to procedures are required for better training outcomes. It is revealed that training modules with excessive interface complexity or poorly optimized workflows will divert the user's focus away from the intended learning objectives, diminishing the overall effectiveness of the training program [45], [46].

Other limitations are related to hardware and network challenges, especially when it comes to multi-user experience and collaborative training. From the hardware side, most XR devices have a restricted FOV and/or lack of physical feedback and ergonomic discomfort from prolonged use of headsets, which can detract from the user experience [41]. For instance, users frequently report fatigue, eye strain, and neck discomfort after extended sessions, which limits the feasibility of long training periods [23], [28], [29]. Besides the utilized hardware, collaborative and multi-user VR and MR systems rely on high-bandwidth, low-latency connections. Thus, any network instability issues or lag can disrupt training, leading to inconsistent user experiences and reduced training effectiveness [47]. Also, multi-user VR and MR applications require robust network setup, which can be difficult to scale for large groups with more than four users [48]. Network synchronization and hardware incompatibilities can hinder seamless collaboration, creating inconsistent experiences among participants. In manufacturing training, where teamwork is often critical, such limitations can impede the effectiveness of group training sessions.

Therefore, this work aims to further study VR and MR environments from a UX perspective in the context of manufacturing training, with the goal of identifying the best setting for assembly task training. To achieve this, two training XR environments (VR and MR) are developed with interactive manufacturing modules on hydrostatic bike design and assembly using Unity Game Engine. The modules are tested with 95 undergraduate students to assess the functionalities and limitations of both environments for manufacturing training. Quantitative data are analyzed using statistical methods, while qualitative data are examined through LDA topic modeling, an NLP approach.

3. XR Environments for Manufacturing Training

Two immersive environments, VR and MR, are designed with an interactive module centered on the assembly tasks of a hydrostatic bike. This bike was chosen for its complex mechanical design and hydraulic circuit, making it suitable for teaching assembly practices. Its mechanical structure, shown in Figure 1, consists of highly coupled subsystems: (A) Front-Lower Assembly, (B) Back-Upper Assembly, (C) Back-Lower Assembly, and (D) the Bike Frame. The comprehensive nature of the bike system allows for the exploration of various UI controls and functionalities within the XR environments by designing assembly and disassembly tasks in multiple phases. These tasks facilitate investigations into system responsiveness to user actions and assessments of visual elements, including textures, image fidelity, and overall quality.

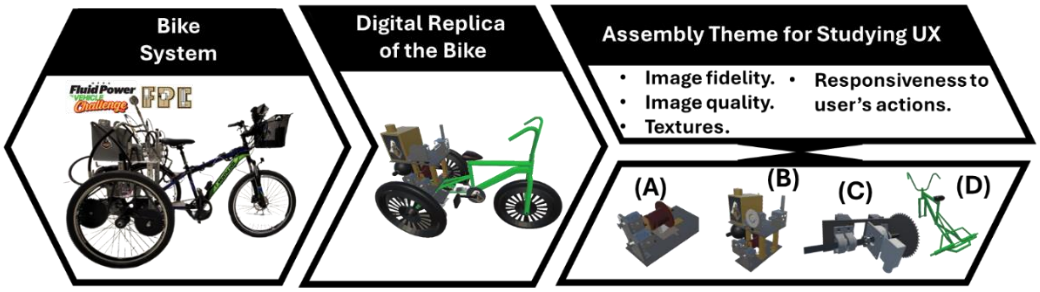

Figure 1. Diagram illustrating the selected mechanical system for the module's theme for the XR environments.

3.1. XR Environment Setup

The two XR environments were designed using the Unity Game Engine [49], incorporating the interactive bike module to test the functionalities and limitations of these XR environments while familiarizing undergraduate students with assembly procedures in manufacturing processes. The following sub-sections introduce the setup procedure and module tasks development in each of the VR and MR environments.

3.1.1. VR setup

Figure 2 illustrates the basic hardware-software integration for the VR setup. The VR environment simulates a realistic virtual manufacturing lab with the interactive assembly module, leveraging the **Oculus Virtual Reality (OVR) Toolkit for Unity** [50].

The immersive 3D lab is designed using the **Warehouse Construction Kit 1.0.1** from the Unity Asset Store [51]. This kit contains over 50 prefabricated assets, such as floors, walls, ceilings, heavy machinery, tools, and merchandise items, which are imported as Unity assets. Then, the 3D models for the bike are designed using CAD tools such as SolidWorks and 3ds Max, which are then converted into FBX format for compatibility with Unity. Once converted, the FBX files are imported into Unity and placed within the scene hierarchy as game objects. Avatars and audio feedback, created using Mixamo and Blender, are also added to the Unity scene, serving as virtual guides to provide instructions.

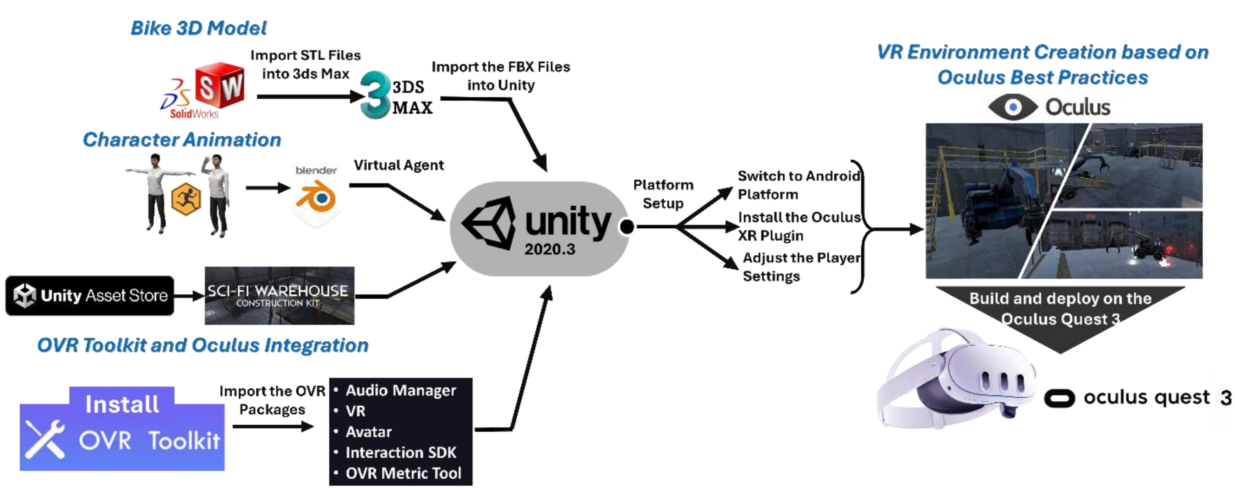

Figure 2. VR Environment Setup (Hardware-Software Integration)

The **OVR Toolkit** [52] is then installed and integrated with the **Oculus XR Plugin** to design the assembly tasks. Additionally, the **Oculus Integration package**, available from the Unity Asset Store, is imported to further enrich the user's interaction. This integration package includes features such as the *audio manager*, *avatars*, and *interaction SDK*, enabling advanced rendering, social features, and avatar interactions. It also supports multitasking by overlaying desktop applications, browsers, and other tools within the VR environment. These capabilities enhance the user experience while performing tasks such as assembly, disassembly, and motion simulation independently without requiring assistance from the developer.

Custom OVR scripts, including "OVRGrabber" and "OVRGrabbable", are configured to enable functions such as object manipulation and hand tracking. Additional scripts, including "OVR Input Module", "Handed Input Selector", and "Laser Pointer", are implemented to enhance interaction and control. For instance, the "OVR Input Module" connects Oculus Touch controllers to the VR environment, allowing users to navigate and interact. The "Handed Input Selector" lets users switch between controlling hands, while the "Laser Pointer" enables remote interaction by simulating a laser for selecting and manipulating objects at a distance. Finally, the Unity platform is then switched to **Android mode**, and the player settings are updated to build and deploy the project to **Meta Quest 3** devices.

3.1.2. MR setup

Figure 3 presents the setup and hardware-software integration for the MR environment design using **Unity 2020.3** and the **Mixed Reality Toolkit 2 (MRTK2)** for Unity [53]. Unlike the VR environment, holographic MR does not require creating a complete virtual scene, as it focuses on augmenting and interacting with virtual objects within the surrounding physical space.

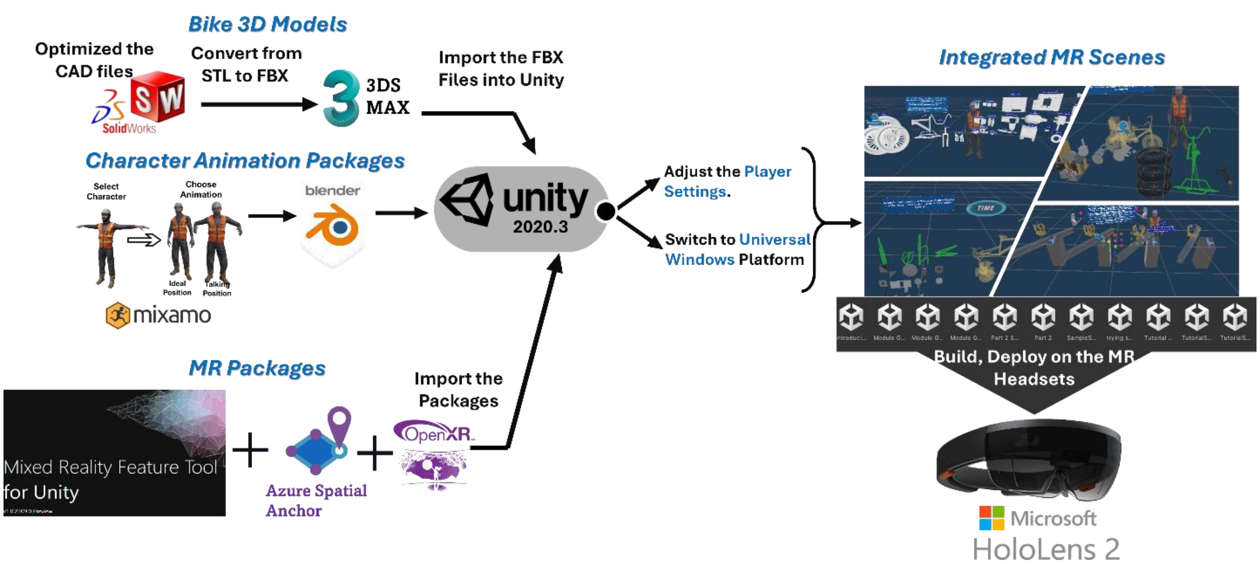

Figure 3. MR Environment Setup (Hardware-Software Integration)

The 3D models of the bike and avatars, along with their animations and simulations, are directly imported into Unity after being optimized with associated physics and simulations using SolidWorks and 3ds Max. Mixamo and Blender are employed to incorporate audio feedback into the animated 3D characters, which act as virtual guides for users completing tasks in the MR environment.

After preparing the 3D models for the MR scene, the **Mixed Reality Feature Tool Kit** application [54] is downloaded to configure the MR playspace. This toolkit enables the installation and integration of standard MRTK packages, including **MRTK Foundations**, **MRTK Extensions**, **MRTK Test Utilities**, and **MRTK Tools**. Additionally, platform-specific packages like the **Mixed Reality OpenXR Plugin** and **Mixed Reality Moving Platform SDK**, as well as **Azure Mixed Reality Services** packages such as **Microsoft Azure Object Anchor** and **Azure Spatial Anchor for Windows**, are added. Once all required packages are imported, the MR playspace is configured by switching Unity to the Universal Windows platform and enabling the OpenXR plugin.

The MR playspace is then divided into several interactive scenes, seamlessly connected using intuitive UI controls, allowing users to navigate between scenes independently. Each scene is designed around specific tasks, including tutorial sessions introducing MR technology and its features, overviews of 3D models, and task-based sections focused on assembly, operations, and mechanisms. Custom Unity scripts are developed and compiled using namespaces such as System.Collections, UnityEngine (e.g., *UnityEngine.Events*), Microsoft.MixedReality.Toolkit (e.g., *Microsoft.MixedReality.Toolkit.Utilities, Microsoft.MixedReality.Toolkit.UI*), HoloToolkit.Unity (e.g., *HoloToolkit.Unity.Buttons, HoloToolkit.Unity.SpatialMapping, HoloToolkit.Unity.InputModule*).

The UnityEngine namespaces provide tools for creating scripts for managing graphics, physics, audio, and UIs, enabling the creation and manipulation of assets, game objects, and scenes. The Microsoft.MixedReality.Toolkit and HoloToolkit namespaces include prefabs, assets, and UI elements needed for MR development, supporting devices like the HoloLens and HoloLens 2. The developed scripts enable interactions such as object grabbing, near and far manipulation, spatial mapping, spatial awareness, eye/hand tracking, and UI controls optimized for HoloLens 2's articulated hand input.

This MR setup successfully creates a spatial environment where users can visualize, interact with, and explore the bike model. Tasks include touching, manipulating, and performing assembly and disassembly operations. Finally, the module is built and deployed on the HoloLens headset.

3.2. Training Module

The bike module in the VR and MR environments is divided into two parts: (1) Tutorial Session and (2) Manufacturing Assembly Process, each featuring a variety of tasks and activities. The tutorial session is designed to familiarize students with the respective XR environment, introducing them to various interactions and UI controls specific to that environment. Following the tutorial, the manufacturing assembly process section engages students in completing a series of tasks aimed at exploring the functionalities, capabilities, and limitations of the VR and MR environments in the context of manufacturing processes. The following subsections present the assigned tasks for both sections (Tutorial Session and Manufacturing Assembly Process) of the module in the VR and MR environments.

3.2.1. Tutorial Sessions

The tutorial sessions introduce students to the principles of virtual and spatial interactions. It prepares them for the manufacturing assembly process section by enhancing their engagement with the assigned tasks. The two tutorial sessions are designed to achieve the same objective, i.e., familiarizing the users with the XR setting; however, they involve distinct tasks due to the unique characteristics of each environment. The following subsections present the tasks incorporated in the VR and MR tutorial sessions.

VR Tutorial Session: For the VR environment, the user's experience relies on using the Oculus Touch, the hand controller for the Oculus (known as the Joysticks), to provide control over the virtual hands, enabling navigation and interaction within the VR environment. Thus, the tutorial session focuses on familiarizing users with Oculus Touch's features, options, and control buttons. It includes a concise guide manual outlining the various buttons and controller options of the Oculus hand controllers, which users must review before proceeding with the tutorial tasks. The VR tutorial incorporates two tasks, shown in Figure 4, (**Task one: Navigation and Interaction with UI controls, and Task two: Object Manipulation - Stacking and Assembly).**

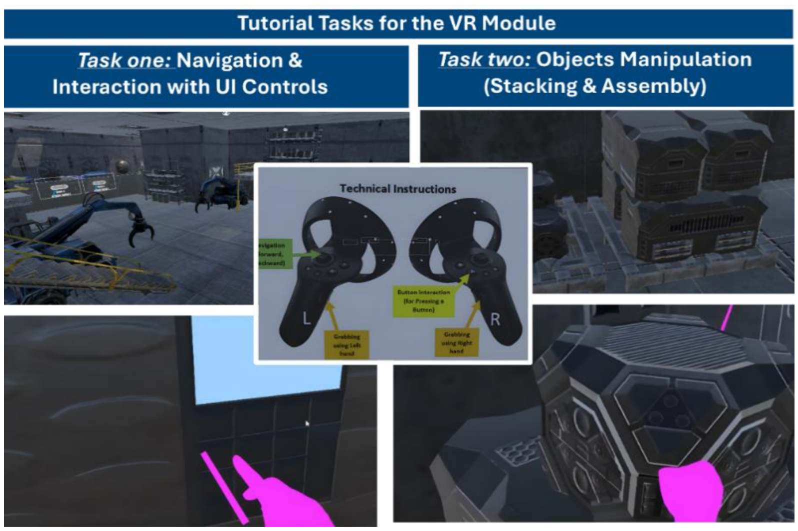

Figure 4. VR Tutorial Session Tasks

Task one introduces users to different navigation techniques within the virtual environment, familiarizing them with the environment's locomotion and UI controls. Users are instructed to navigate the environment using the control buttons of Oculus Touch, such as walking around different stations and moving upstairs/downstairs. Visual aids, such as colorful arrows, are provided to guide users during this task, enhancing their experience. Users are also required to interact with virtual UI control panels by utilizing the real buttons on Oculus Touch. Therefore, task one exposes users to fundamental navigation methods and Oculus Touch, enabling them to synchronize their virtual actions with real-world counterparts. **Task two** introduces users to the manipulation and grabbing techniques through a short stacking and assembly activity. Users are asked to stack objects in a predefined sequence by grabbing, handling, and lifting items using their virtual hands. Users must use the Oculus Touch controllers utilizing the techniques learned in task one to control the opening and closing of their virtual thumb and fingers to grab/manipulate the virtual objects. Task two further familiarizes users with the Oculus Touch, especially grabbing buttons, preparing them for the assembly section after the tutorial.

MR Tutorial Session: MR tutorial emphasizes the basic principles of spatial interaction required for completing tasks in the manufacturing process section. It consists of two tasks **(Task One: Object Manipulation (Assembly) and Task Two: UI Controls),** as illustrated in Figure 5.

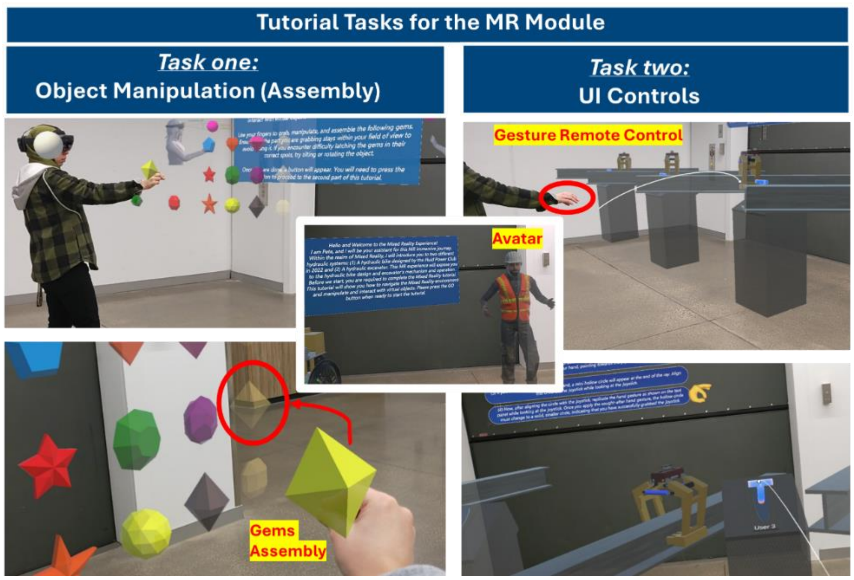

Figure 5. MR Tutorial Session Tasks

Task one introduces users to object manipulation techniques within a controlled MR framework by assembling virtual gems. Participants are tasked with assembling and snapping these virtual assets (gems) using actions such as grabbing, pointing, rotating, and scaling. These activities help users develop the required manipulation skills for the subsequent section. Instructional guidelines are provided through hand gestures and voice commands, enhancing the user experience and simplifying the process. Successfully completing this task equips users with the skills necessary for the manufacturing assembly section.

Task two focuses on teaching users basic UI controls, including near and far manipulation techniques, i.e., interacting with the virtual assets at varying distances and adapting to different user postures like standing, sitting, or reaching. Students use virtual UI controls, like push buttons, sliders, and joystick, to control a mechanical system (a gripper end-effector in our case) from a distance, employing the far manipulation technique within the MR environment. The task requires users to remotely interact with the virtual joystick to open/close the gripper for lifting a virtual I-beam from a far distance in a standing position. Step-by-step instructions are provided through avatars, visual displays, hand gestures, and voice commands, ensuring clarity and ease of learning. For example, users are first instructed to extend one hand and point it at the virtual joystick. This action generates a ray with a hollow circle from their hand, which they must align with the joystick. Next, users replicate a specific hand gesture displayed on a virtual instruction panel to grab the joystick. Once the joystick is successfully grabbed, the hollow circle changes to a solid circle, indicating a secure hold. Users then move their hands forward and backward to control the joystick, which in turn operates the gripper's end-effector to lift the I-beam. Task Two helps users learn different manipulation techniques.

3.2.2. Manufacturing Assembly Process Tasks

The manufacturing assembly process section in each of the VR and MR modules comprises three basic tasks **(Task One: Components, Task Two: Sub-system Assembly, and Task Three: Entire System Assembly),** shown in Figure 6. Task one aims to explore the visual functionalities and limitations in each XR environment, task two asses the responsiveness and user interaction during assembly tasks, and task three studies user interaction during complex assemblies. The overall objective of the three tasks is to evaluate UX from the system's responsiveness to visual functionalities within each of the XR settings in the context of teaching manufacturing assembly tasks.

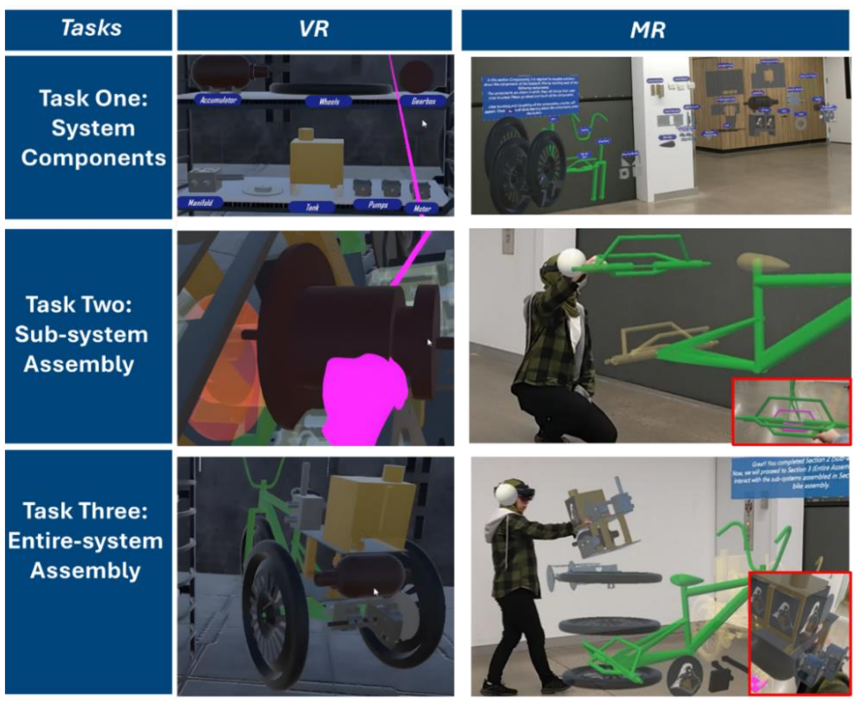

Figure 6. Manufacturing Assembly Section Tasks

Task one is designed to investigate the visual capabilities and constraints of the XR environments by focusing on interactions with the bike components' materials and textures. Students are required to virtually engage with the individual components of the bike (up to 45 components), studying their technical details and material properties. Visual cues, such as color changes, are incorporated into the task to provide immediate feedback on user interactions while enhancing user engagement and comprehension of material properties. This task allows the evaluation of the UX in manufacturing education by identifying issues such as insufficient visual feedback or unclear material representation, which could impact the students' understanding of component details. It enables educators to assess how effectively students can interact with and interpret virtual representations of manufacturing components in both VR and MR environments.

Task two evaluates the responsiveness of the XR environments to user actions while teaching the basic assembly of bike sub-systems. This task builds on the hand interaction techniques introduced during the tutorial sessions, requiring users to assemble bike sub-systems virtually. It enables the study of the system's responsiveness and usability during manufacturing assembly by examining control events, time delays, and potential discomfort. From a UX perspective, the task is critical for identifying challenges students might face when performing assembly procedures, such as difficulty in aligning parts or experiencing delayed feedback. The task outcomes are essential for improving the usability and effectiveness of XR-based manufacturing training tools, ensuring that students can seamlessly learn and execute assembly processes in both environments.

Task three focuses on assembling the complete bike by integrating the previously assembled sub-systems. Students must utilize the grabbing and manipulation techniques introduced during the tutorial to control and position the sub-systems, completing the final assembly. This task provides a comprehensive evaluation of user interaction with complex assemblies in VR and MR settings during manufacturing assembly. It enables educators to study how effectively students apply the learned techniques to complete an intricate manufacturing assembly task. From a UX standpoint, this task highlights challenges such as difficulty in handling multiple sub-systems, inconsistencies in control precision, or discomfort during prolonged interactions. The findings from this task help refine the XR environments, leading to the selection of the best environment that supports teaching assembly procedures and addresses potential barriers to student learning.

Therefore, the integration of these tasks allows for a thorough assessment of the UX in the context of manufacturing education, particularly when teaching assembly procedures. The tasks provide valuable data on the strengths and limitations of each XR environment by targeting visual interaction, system responsiveness, and complete assembly processes, helping to identify and address issues students might encounter. This enables the selection of the optimal and user-friendly XR environment for manufacturing training.

4. Research Study

After the development of the two XR environments and the associated manufacturing assembly module, a research study is conducted to evaluate their effectiveness, providing answers to RQ1 and RQ2. The study involved 95 undergraduate engineering technology students (84 males and 11 females) enrolled in Fluid Power course at Purdue University. An institutional review board (IRB) application is prepared and approved (IRB-2023-1894) for the study. Survey questionnaires are designed and administered to assess the capabilities, features, functionalities, and limitations from a UX aspect of both environments in the context of manufacturing training.

All participating students experienced the interactive VR and MR environments, completing the associated manufacturing assembly tasks and surveys during a lab session. The following subsections present the survey design and the experimental setup.

4.1. Survey Questionnaires

A combination of qualitative and quantitative data collection tools is utilized, including pre-and post-survey questionnaires (see Table 1 and Table 2), which are designed, tested, and validated through a university review board. The review process involved research experts from various fields, including XR design, manufacturing engineering education, and data analytics, to ensure that the surveys provide a comprehensive evaluation of the technical performance and UX of the XR environments and their potential impacts on safety and usability.

The pre-survey, shown in Table 1, includes three questionnaires designed to acquire data on students' socio-demographics (Q1), educational backgrounds (Q2), and prior experience with XR technologies (Q3). The socio-demographic questions (Q1.1, Q1.2, and Q1.3) collect information on students' age, gender, and ethnicity, which helps generalize the study's findings across diverse demographic groups. The educational background questions (Q2.1, Q2.2, and Q2.3) collect data about students' academic qualifications, such as their highest degree earned, major, field of study, and current educational status. This information is required for analyzing potential correlations between students' academic backgrounds and their responses to the survey. In addition to the Q1 and Q2 questionnaires, questionnaire Q3 involves two semantic differential questions (Q3.1 and Q3.2) to assess students' familiarity and expertise with XR environments. These questions focus on collecting data regarding the students' prior experience with VR and MR technologies before the experiment. Responses are measured on a 1 to 5 bipolar scale (1: Very Unfamiliar, 2: Unfamiliar, 3: Moderately Familiar, 4: Familiar, and 5:Very Familiar). Collecting this information enables us to evaluate the learning curve associated with each technology. It also allows us to explore the students' levels of adaptation to VR and MR environments by comparing their task performance based on their varying levels of familiarity with these technologies.

Table 1. Pre-Survey Questionnaire

Three Pre-Survey Questionnaire					
Q1: Socio-demographic					
Q1.1	Specify your age.				
	18-20	*21-23*	*24-26*	*27-29*	*Above 29*
Q1.2	Specify your sex.				
	Male	*Female*	*Other (Specify)*	*Prefer not to Say*	
Q1.3	Specify the ethnicity that you identify the most.				
	Asian American	*African American*	*Hispanic*	*White/Caucasian*	*Other (Specify)*
Q2: Educational background					
Q2.1	What is your highest degree?				
Q2.2	What is your major?				
Q2.3	What is your current educational status?				
Q3: Level of experience with XR environments					
Q3.1	What is your experience with Virtual Reality (VR)? Note: The VR setting is where the user interacts with virtual assets in an immersive virtual environment.				
	1 = Very Unfamiliar to 5 = Very Familiar				
Q3.2	What is your experience with Mixed Reality (MR)? Note: The MR setting is where the user interacts with virtual assets in the real tangible world.				
	1 = Very Unfamiliar to 5 = Very Familiar				

The post-survey, shown in Table 2, consists of four questionnaires (Q1, Q2, Q3, and Q4). Questionnaires Q1 and Q2 focus on assessing the technical aspects of the XR environments, while Q3 and Q4 evaluate the environments' impact on students' overall experiences.

Table 2. Post-Survey Questionnaire

Four Post-Survey Questionnaire		Anchors of the Scale
Questionnaires on the Technical Aspects of the XR Environments		
Q1: Visualization and system replication		
Q1.1	Focusing on visualization, which setting helped you the most in visualizing the internal structure of the systems involved in the assigned tasks (disregard discomfort and motion sickness)?	1= VR 2= MR
Q1.2	Which setting gave you control over the real surroundings besides interacting with the virtual assets?	
Q1.3	Which setting best replicated the systems involved in the assigned tasks?	
Q2: System responsiveness and interaction		
Q2.1	How responsive were each of the two settings (VR and MR) to actions that you Performed?	*For each (VR and MR):* 1= Not at all, 5= Very Well
Q2.2	How natural did your interactions with the environment feel (VR and MR)?	
Q2.3	How proficient in moving and interacting with each of the two environments (VR and MR) did you feel at the end of the experience?	
Questionnaires on the Environments' Impact on User		
Q3: Discomfort and adaptation		
Q3.1	How would you rate the level of discomfort, like motion sickness, eyestrain, etc., you encountered in the VR and MR settings?	*For each (VR and MR):* 1 = Very Low, 5 = Very High
Q3.2	How would you rate the speed of your adaptation to the experiences in the VR and MR settings?	
Q4: Textual questions on safety awareness		
Q4.1	Did you experience physical or mental challenges or fatigue while performing the task in the two settings? Please explain for each: (a) VR and (b) MR	
Q4.2	Are there any user safety concerns associated with the two settings? Please explain for each (a) VR and (b) MR	

Q1 questionnaire, which consists of three questions (Q1.1, Q1.2, and Q1.3), compares the visualization and visual aids provided by the VR and MR environments. These questions are structured on a two-option scale (1: VR, 2: MR) to identify preferences between the two technologies. Q2 questionnaire comprises three semantic differential questions (Q2.1, Q2.2, and Q2.3) that assess the impact of the environments' effectiveness on user actions. Responses are measured on a 1 to 5 bipolar scale (1: Not at all, 2: Fair, 3: Moderate, 4: Well, and 5:Very Well), enabling an evaluation of responsiveness in both XR environments. Q3 questionnaire consists of two semantic differential questions (Q3.1 and Q3.2). Q3.1 examines the discomfort experienced by the students in XR environments, while Q3.2 evaluates the ease of students' adjustability to the XR environments. Q3.2 also allows for a comparison of learning curves between the two environments, taking into account the familiarity data collected in the pre-survey. Both questions use a 1 to 5 bipolar scale (1: Very Low to 5: Very High) to assess user adaptability and comfort levels in the two XR environments. Finally, Q4 questionnaire includes two short-text questions (Q4.1 and Q4.2) that address safety concerns within the XR environments. These questions explore students' physical and mental challenges during task completion and investigate any potential safety issues related to the use of VR and MR technologies in the training modules.

4.2.Experimental Design

The research study involves 95 undergraduate engineering technology students enrolled in Fluid Power course. The students are divided into seven sections, each consisting of 13 to 14 students, and each section is allocated a total of two hours. Five Meta Quest 3 VR headsets and five HoloLens 2 MR headsets are utilized throughout the study. The experimental process is outlined in Figure 7.

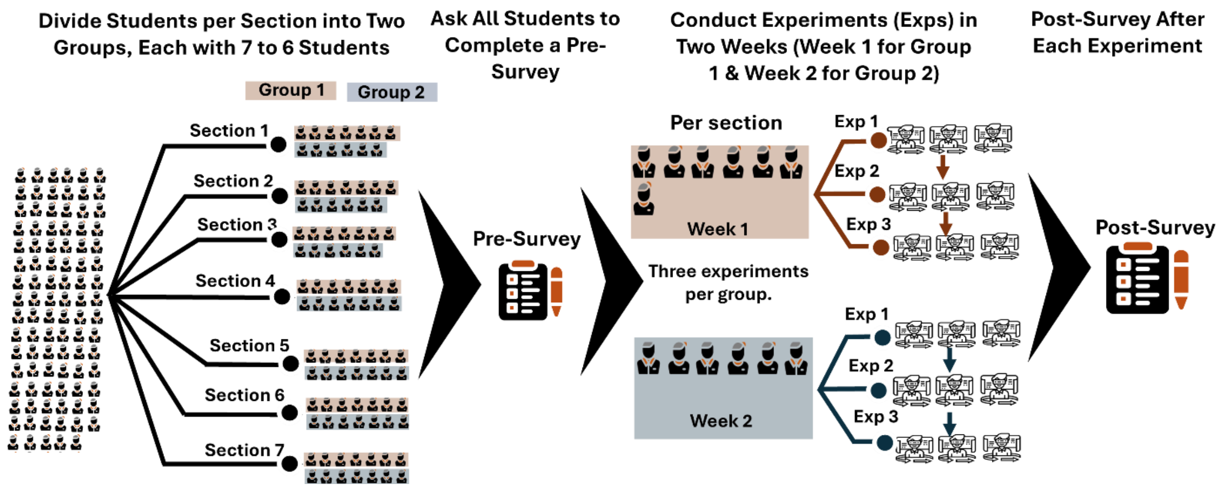

Figure 7. Experimental Setup

Each section is further divided into two groups (Group 1 and Group 2), with six to seven students per group. Prior to experiencing the XR environments, all students are asked to complete the pre-survey questionnaires. Then, the experiments are conducted over two consecutive weeks to accommodate the number of students. During Week 1, experiments for Group 1 in all seven sections are completed, while in Week 2, experiments for Group 2 are conducted.

Each experiment consists of students experiencing both XR environments and completing the assigned module tasks, consisting of a tutorial session and the manufacturing assembly processes. For each group, three students initially experienced the MR environment and its associated module and then proceeded to the VR environment, completing the same activities simultaneously but independently. Figure 8 shows two different groups interacting with the XR environments during the study.

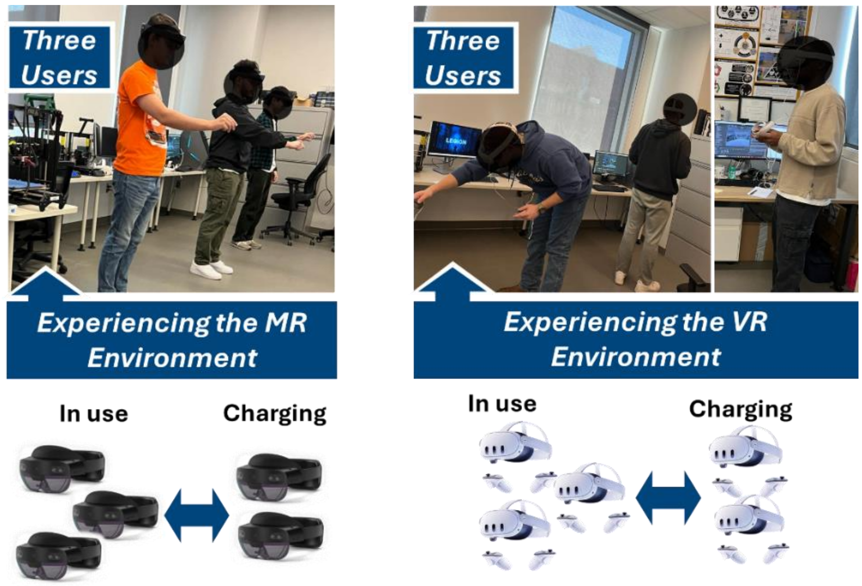

Figure 8. Two different groups, each consisting of three students, experiencing the MR and VR environments in LMBS 4258.

Three Meta Quest 3 VR headsets and three HoloLens 2 MR headsets are used in each experiment, while the remaining headsets are charged in preparation for subsequent sessions. After completing their assigned tasks, students are requested to fill out the post-survey questionnaires on Qualtrics. As the first set of students completes the post-surveys, the other set begins their experience with the XR environments. This alternating process ensures that all participants have the opportunity to engage with both VR and MR environments. The same procedure is applied consistently across all groups and sections, ensuring comprehensive participation while managing the study and data collection. After completing the data collection, the quantitative and qualitative data are cleaned and sorted to be ready for analysis and evaluation.

4.3.Data Analytics Tools

The quantitative and qualitative data are analyzed using statistical and NLP methods. Quantitative data obtained from semantic differential questions are analyzed using descriptive statistical methods, specifically mean and standard deviation comparisons.

In contrast, textual responses to short-answer questions are analyzed semi-automatically using NLP techniques, specifically LDA topic modeling approach. The LDA is a probabilistic generative model commonly applied in various studies to identify topics within large textual datasets [55]–[57]. The LDA model detects latent topics in text data without requiring pre-labeled information [58], by representing each document as a composition of topics, where each topic consists of a collection of words ranked by their probability weights.

Throughout this study, the LDA model is used to identify key themes within students' textual responses, providing detailed answers to the short-answer questions. The LDA analysis is conducted using MATLAB's Text Analysis Toolbox, which includes algorithms and visualization tools for preprocessing, analyzing, and modeling text data. The toolbox enables the selection of the optimal number of topics (*n*) by generating a perplexity model for each dataset. Perplexity serves as a measure of how well the model describes the data, with lower perplexity values (below 200) indicating a better model fit. This approach ensures the determination of the optimal number of topics (n) required to develop the LDA topic models.

Based on the perplexity model, the optimal number of topics is identified for generating LDA topic models. For each topic, the model produces a set of 10 to 20 representative words, ranks them by their associated probabilities, and assigns a weight to each topic. These probabilities define the overarching theme of each topic, with the prominence of a theme reflecting its relevance within the dataset. This method enables the identification of comprehensive themes that address the short-answer questions effectively.

5. Data Analysis and Results

The following subsections present the analysis results for a subset of the collected data, specifically the pre-survey data and the Q1, Q3, and Q4 questionnaires of the post-survey.

5.1. Statistical Descriptive Analysis

This section presents the statistical analysis results of the data acquired from students' responses to *Q1: Visualization and System Replication* in the post-survey, which assesses the **technical aspects of the XR environments**. It also presents the analysis of students' responses collected from *Q3: Discomfort and Adaptability* in the post-survey, examining the **impact of XR environments on users post-experiment while exploring their familiarity with XR pre-experiment**, acquired from *Q3: Level of Experience with XR Technologies* from the pre-survey.

5.1.1. Technical Aspect of the XR Environments: Visualization and System Replication

Table 3 and Figure 9 present the results of questionnaire Q1 of the post-survey, which aims to study one of the technical aspects of the XR environments, specifically visualization and system replication. Table 3 indicates that questions Q1.1, Q1.2, and Q1.3 have high mean values (above 1.5). Specifically, questions Q1.2 and Q1.3 have the highest mean values **(M =1.71, SD = 0.21)**, indicating that 71% of the students (67 out of 95, as shown in Figure 9) preferred "MR" over "VR". Similarly, question Q1.1 exhibits a high mean **(M = 1.69, SD = 0.46)**, comparable to the values of Q1.2 and Q1.3, showing that 69% of the students, as illustrated in Figure 9, found "MR" to be more convenient for system visualization and representation.

The findings indicate that the MR setting is considered most suitable for system representation compared to VR, knowing that the same assets for the bike are utilized for the module tasks. The results indicate that the visual functionalities of MR environments, such as spatial mapping, spatial anchoring, object augmentation, object tracking, and holographic features, provide users with a degree of controllability over the physical surroundings and improve the accuracy of the virtual assets' replication and augmentation within the environment.

Table 3. Mean and Standard deviation of Q1 from the post-survey that aims to assess the technical aspect of the XR environments, targeting visualization and system replication.

Questionnaire Q1 from the post-survey	VR	MR	M (Mean)	SD (Standard Deviation)
Q1.1) Focusing on visualization, which setting helped you the most in visualizing the internal structure of the systems involved in the assigned tasks (disregard discomfort and motion sickness)?	1	2	1.69	0.46
Q1.2) Which setting gave you control over the real surroundings besides interacting with the virtual assets?	1	2	1.71	0.21
Q1.3) Which setting best replicated the systems involved in the assigned tasks?	1	2	1.71	0.21

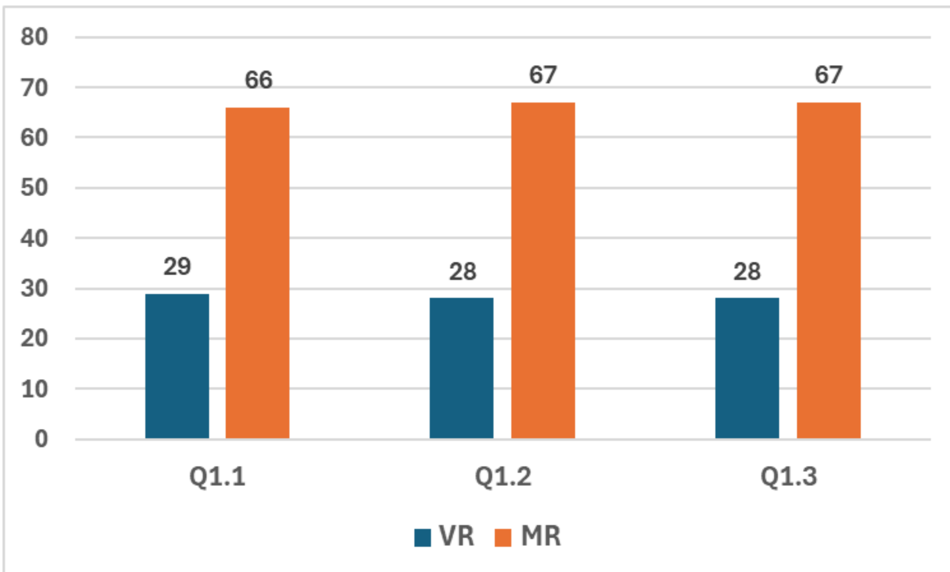

Figure 9. Statistical diagram illustrating the data collected from the students' responses to the post-survey questionnaire Q1.

5.1.2. Environments' Impact on Users: Students' level of experience with XR pre-experiment and their level of adaptability post-experiment

Table 4 and Figure 10 illustrate the results of questionnaire Q2 of the pre-survey related to understanding students' experience and familiarity with each of the VR and MR. The results in Table 4 reveal that Q3.2 has the lowest mean value (M= 2.52, SD= 1.07), indicating that 52% of the participants, as shown in Figure 10, were unfamiliar with the MR technology before experiencing the module. As shown in the figure, 49 out of the 95 students' responses (52%) to Q3.2 range between "Unfamiliar" and "Very Unfamiliar", 29 out of 95 (31%) are "Moderate", and the remaining (17%) is divided between "Certain" and "Very Certain". Thus, around half of the participants (52%) did not have prior experience with MR, 31% had a fair experience with MR, and the rest (43%) were familiar with using MR. Question Q3.1 has a moderate mean value (M= 3.25, SD= 1.23), indicating that 49 out of 95 of the students, as reported in Figure 10, had moderate to good experience with VR. Figure 10 shows that 27 out of 95 (28%) had a moderate experience with VR, and 41 out of 95 (43%) were already familiar with VR.

Table 4. Mean and Standard deviation of Q3 from the pre-survey that aims to study the students' level of experience and familiarity with VR and MR.

Questionnaire 3 from pre-survey	Very Unfamiliar	Very Familiar	M (Mean)	SD (Standard Deviation)
Q3.1) What is your experience with Virtual Reality (VR)? (In other words, select the level of familiarity with MR)	1	5	3.25	1.23
Q3.2) What is your experience with Mixed Reality (MR)? (In other words, select the level of familiarity with MR)	1	5	2.52	1.07

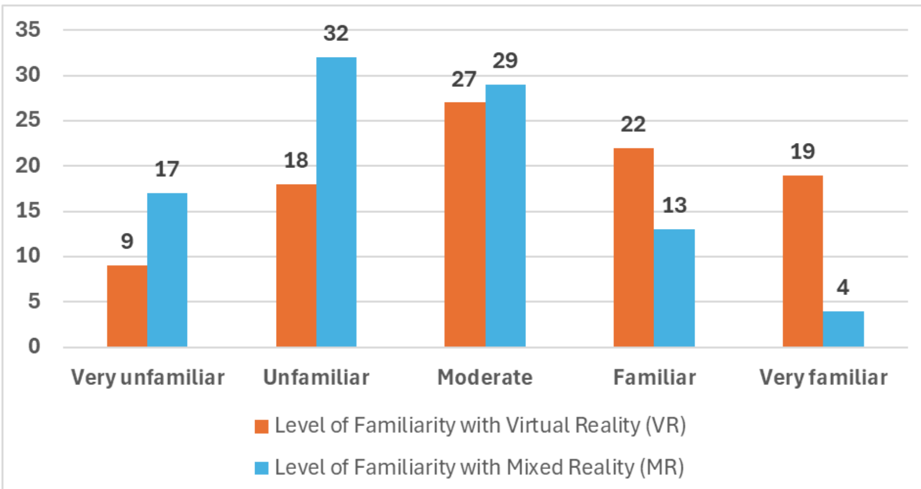

Figure 10. Statistical diagram illustrating the data collected from the students' responses to the pre-survey questionnaire Q3.

These results allow us to compare the familiarity of VR versus MR before the module experience as follows. **Familiarity with MR**: 52% of students were unfamiliar with MR, 31% had a fair experience with MR, and 17% were already familiar with MR. **Familiarity with VR**: 43% were already familiar, 29% had no experience with VR, and 28% had a moderate experience with VR. Thus, the data indicates that students were more familiar with VR than with MR, and this is supported by the fact that VR is more prevalent and accessible for users than MR.

Error! Reference source not found. shows the results of the questionnaire Q3 (Q3.1 and Q3.2) o f the post-survey. Question The results of Q3.1 reveal that 94% of the students, i.e., 89 out of the 95, reported low to very low levels of discomfort, e.g., headache, eyestrain, motion-sickness, etc., within the MR setting, where 68% responded "Very Low" and 26% responded "Low" to Q3.1. The rest is divided as 4% for "Fair" and 2% for "High". However, around half of the students (49%) reported high to very high levels of discomfort within the VR setting, 20% reported a fair level of discomfort, and the rest (31%) reported low to very low levels. The results of Q3.1 indicate that the MR setting has a potential benefit over the VR setting in terms of user comfort. The results are supported by the nature of the MR environment, which utilizes holographic head-mounted displays to minimize motion sickness within the environment.

The results of Q3.2 within the MR environment reveal that 79 out of the 95 students (83%) reported “Very High” and “High”, 13 students (14%) reported “Fair”, and the rest of the students (3%) reported “Low”. The results indicate that the majority of the students (83%) were able to adapt to the MR environment quickly. In contrast, the results of Q3.2 within the VR setting reveal that 48 out of the 95 students (51%) reported “Very High” and “High”, 23 students (24%) reported “Fair”, and the rest of the students (25%) reported “Low”. Thus, half of the students faced challenges adapting to the VR setting.

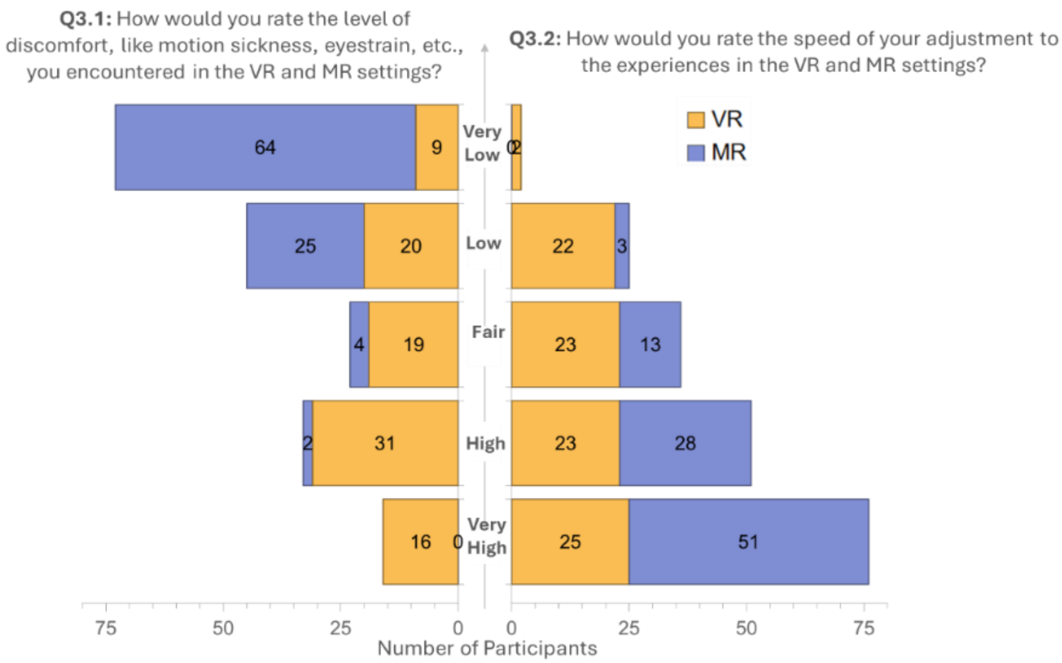

Figure 11. Statistical diagram illustrating the data collected from the participants’ responses to the post-survey questionnaire S2 Q2.

Recalling that the % of students unfamiliar with MR (52%) was higher than those unfamiliar with VR (29%) indicates that the MR interface is more convenient for users with no prior experience with MR technology. Despite a significant portion (52%) of participants unfamiliar with MR, a large majority (83%) reported high adjustability within the MR environment. In contrast, although fewer participants (29%) were unfamiliar with VR, 51% faced issues trying to adapt to the VR setting. Therefore, the findings reveal that MR interfaces are more intuitive and user-friendly for users without prior MR experience compared to VR settings, which present more challenges in adapting to the setting.

5.2. LDA Topic Modeling Analysis

The students’ responses to the safety awareness questionnaire Q4 are analyzed using LDA topic modeling, where a perplexity model is generated to determine the optimal number of topics *(n)*, as outlined in Section 4 (Data Analytics Tools). For each identified topic, a list of the top 10 to 20 defining words, along with their associated probabilities, is visualized using word clouds. These word clouds served as a basis for deriving topic themes, indicating how the topics are represented within the dataset. The following subsections present the findings for the two questions, Q4.1 and Q4.2.

5.2.1. LDA topic Modeling for Q4.1

Students' responses to Q4.1, which explores potential physical or mental challenges experienced during manufacturing assembly tasks in VR and MR environments, are first cleaned to correct typos, divided into two datasets: (a) VR and (b) MR, and underwent LDA topic modeling. The results are shown in Figure 12, Figure 13, and Table 5. To determine the optimal number of topics (n), a perplexity model is first generated for each dataset (VR and MR), identifying the optimal LDA topic models to interpret the students' responses. The perplexity models for datasets (a) and (b) are shown in Figure 12. The models reveal that the optimal number of topics for a good fit to the data is between seven and eight for both the VR and MR datasets.

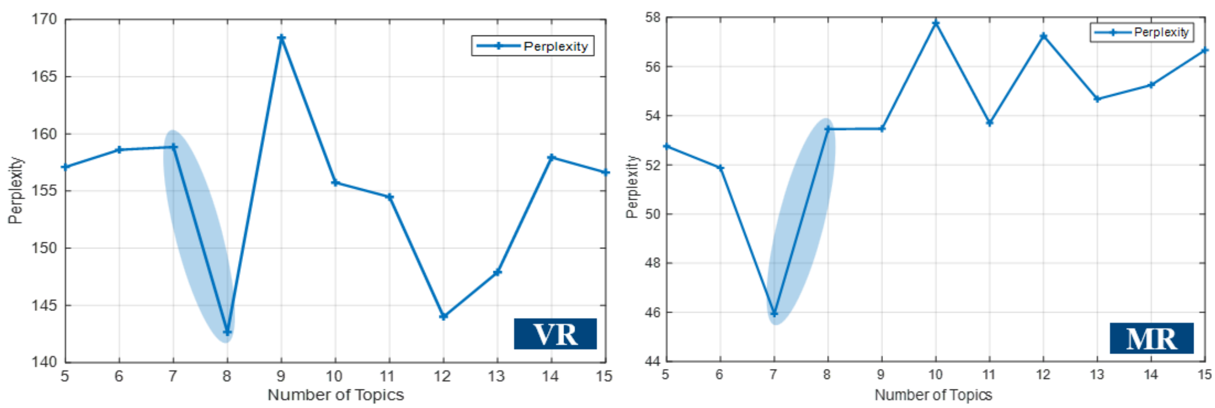

Figure 12. Perplexity Models generated for Q4.1

Based on the results of the perplexity models, eight topics are generated for each dataset. For each of the eight topics in both datasets, the top 20 words that best represent the topic are generated, along with their corresponding topic weights. Additionally, the probability associated with each word within a topic is computed, and the results are visually shown in word clouds shown in Figure 13. The word clouds illustrate the top 20 words from each dataset, with font sizes varying according to the words' probabilities within the dataset. For instance, words with the highest probabilities are displayed in larger font sizes and highlighted in orange for emphasis. The word clouds assist in generating the topic themes (LDA topic model) for both datasets, as shown in Table 5.

Figure 13. Generated world clouds for the two datasets (a) VR and (b) MR for Q4.1

Table 5. Topics generated using the LDA Topic Model for Q4.1

LDA Topic Model for Students' Responses to Q4.1 *Did you experience physical or mental challenges or fatigue while performing the task in the two settings? Please explain for each: (a) VR and (b) MR*			
(a) For VR			
Topic #	***Normalized Topic Weight***	***Top 20 Topic Words or less***	***Topic Theme***
1	11.7 %	none, experience, felt, getting, sick, trying, turning, object, walking, desk, around, uncomfortable, parts, virtual, kind, VR, nauseous, head, movement, physical	Experiencing uncomfortable physical movement and nausea in VR.
2	14.9 %	headset, moving, motion-sickness, motion, lot, feeling, sickness, got, experience, slight, felt, challenges, like, physical, movement, made, dizzy, uncomfortable, trying, mental	Motion sickness caused by uncomfortable movement in the VR environment.
3	15 %	Motion-sickness, motion, little, order, get, bit, sickness, challenges, made, balance, setting, headset, caused, mental, difficult, parts, dizzy, make, smoothened, due	Motion sickness while trying to balance mental and physical strain.
4	11.4 %	Motion-sickness, fatigue, moving, bit, like, movement, lots, made, myself, sure, minor, mentally, anything, causing, little, place, physical, around, challenges, location	Motion sickness and fatigue because of movement and navigation within the VR
5	12.4 %	little, experience, hand, real, around, sickness, move, caused, down, motion-sickness, difficult, headset, slight, setting, challenges, moving, physical, mental, got, overall	Challenges with moving around the setting caused slight motion sickness
6	11.9 %	experience, headset, bit, motion, difficult, feel, mental, vertigo, motion-sickness, setting, caused, real, sick, movement, dizzy, challenges, brain, concern, possibly, confused	Brain confusion caused by the headset leading to motion sickness and dizziness
7	11.8 %	little, fatigue, problem, controls, kept, mental, difficult, space, made, motion-sickness, might, moving, complete, motion, challenges, dizziness, feeling, world, sickness, stomach	Control issues and spatial disorientation caused motion challenges, leading to dizziness and feeling sick
8	10.8 %	disorienting, motion, experience, little, issues, motion-sickness, weird, visual, experienced, sweaty, world, around, snap, bad, just, overall, uncomfortable, dizzy, felt	Disorienting uncomfortable motion caused dizziness and motion-sickness, making the experience a little bad
(b) For MR			
Topic #	***Normalized Topic Weight***	***Top 20 Topic Words or less***	***Topic Theme***
1	11.7 %	none, MR, felt, motion, experience, fatigue, grabbing, VR, sometimes, objects, bit, physical, two, headache, issue, onset, stuck, completing	None, only a bit of fatigue while grabbing objects
2	21.9 %	none, MR, experience, challenges, little, smooth, away, gave, mental, bit, immediately, snap, glitch, sickness, weren't, operation, fatigue, head, thought, manipulate	No challenges in the MR experience, as it was a smooth operation
3	12.63 %	None, field, view, fun, MR, easy, mental, comfortable, components, difficult, little, get, lab, down, better, parts, right	MR was fun and easy with little difficulty in getting the parts in the right location.

4	6.2 %	challenges, felt, experience, smooth, fatigue, lot, away, comfortable, just, issues, things, around, space, none, properly, user, almost, discomfort, present, orienting	The experience was comfortable
5	10.4 %	MR, none, frustrating, set, sickness, hands, challenges, enjoyed, sometimes, space, lose, limitation, everything, looked, frame, track	Frustration tracking the hands, but I enjoyed the MR
6	10.1 %	MR, physical, work, felt, operating, weren't, smooth, easy, issue, mental, deal, working, annoying, try, extension, experienced, natural, straining	Working with MR experience was easy and smooth and felt natural
7	19.4 %	MR, none, experience, fatigue get, up, felt, smooth, easy, annoying, deal, operation, shafts, wrong, easier, direction, bearings, sometimes, align	No challenges: MR was easy and smooth; however, aligning the bearings and shafts sometimes felt annoying
8	7.8 %	MR, real, thought, physical, components, experience, physically, just, times, mental, little, time, difficult, felt, hard, challenges, working, really, lab, little	MR felt a little difficult dealing with components

LDA topic model for the (a) VR dataset:
The topic weights of the VR dataset, presented in Table 5(a), indicate that the eight topics are evenly distributed based on their importance across the dataset, with each topic contributing approximately equally to the overall distribution. Among these, topics two and three (highlighted in light green) got the highest topic weights. These topics reveal that students frequently experienced motion sickness during the VR experience, attributing it to the discomfort of the VR headset and the effort required to manage both mental and physical strain. Other topics also emphasize physical challenges, such as motion sickness, eyestrain, and headaches, which students associate with brain confusion resulting from transitioning between the physical and virtual worlds. Additionally, the results indicate that students experienced disorientation due to the perception of movement in the virtual environment while remaining physically stationary in the real world.

LDA topic model for the (b) MR dataset:
In contrast to the evenly distributed topic weights of the (a) VR dataset, the topic weights of the (b) MR dataset show variation, indicating that certain topics are more prevalent than others. For example, topic two has the highest weight, making it the most dominant topic in the dataset, followed by topic seven. On the other hand, topics four and eight (highlighted in light yellow) have the lowest weights, indicating they are less significant within the dataset. The themes of the dominant topics indicate that most students reported smooth and enjoyable experiences with minimal challenges. However, some students experienced fatigue and physical discomfort, primarily due to technical issues encountered during specific tasks and limitations associated with the MR hardware.

5.2.2. LDA topic Modeling for Q4.2

Similarly, students' responses to Q4.2, which aimed to investigate safety concerns during the manufacturing assembly tasks in VR and MR environments, are analyzed following the same procedure applied to Q4.1. The results are presented in Figure 14, Figure 15, and LDA topic ***model for the (a) VR dataset:***

The results of the LDA topic model generated for the VR dataset indicate that the topics are evenly distributed and exhibit almost the same importance. Topic five has the highest topic weight, followed by topic seven, making these two topics the most prominent topics. The topic themes assigned for topic five exhibit safety concerns related to the room space in the VR environment, emphasizing the importance of spatial awareness and freedom of movement. The theme of topic seven reveals physical risks, such as collisions with desks and computers despite virtual boundaries, showing challenges in maintaining physical safety during VR experiences. The remaining topics address other safety concerns associated with VR settings, including collisions with surrounding objects, spatial awareness issues, and the limitations of virtual boundaries in ensuring user safety.

LDA topic model for the (a) MR dataset:

The results of the LDA topic model generated for the MR dataset reveal that topics five and six, highlighted in light green, emerge as the dominant themes within the model due to their highest topic weights. The themes indicate that students perceived the MR environment as safe without observing safety concerns or risks. For instance, topic five is pivoted on the absence of safety concerns, indicating that the nature of the MR environment and the ability to manage the physical world adds no safety concerns. Topic six also emphasizes the lack of safety concerns when the surrounding environment is empty, emphasizing the importance of having an empty, unobstructed environment for ensuring safety. The remaining topics share similar importance following topics five and six, as they have an even distribution of topic weights within the LDA topic model. These topics further emphasize the absence of major safety concerns within the MR environment, with minor issues such as eye strain.

Table 6. Based on the perplexity models shown in Figure 14, seven topics are generated for each dataset with the world clouds (Figure 15), topic weight, top 20 words, and assigned topic theme (LDA topic ***model for the (a) VR dataset:***

The results of the LDA topic model generated for the VR dataset indicate that the topics are evenly distributed and exhibit almost the same importance. Topic five has the highest topic weight, followed by topic seven, making these two topics the most prominent topics. The topic themes assigned for topic five exhibit safety concerns related to the room space in the VR environment, emphasizing the importance of spatial awareness and freedom of movement. The theme of topic seven reveals physical risks, such as collisions with desks and computers despite virtual boundaries, showing challenges in maintaining physical safety during VR experiences. The remaining topics address other safety concerns associated with VR settings, including collisions with surrounding objects, spatial awareness issues, and the limitations of virtual boundaries in ensuring user safety.

LDA topic model for the (a) MR dataset:

The results of the LDA topic model generated for the MR dataset reveal that topics five and six, highlighted in light green, emerge as the dominant themes within the model due to their highest topic weights. The themes indicate that students perceived the MR environment as safe without observing safety concerns or risks. For instance, topic five is pivoted on the absence of safety concerns, indicating that the nature of the MR environment and the ability to manage the physical world adds no safety concerns. Topic six also emphasizes the lack of safety concerns

when the surrounding environment is empty, emphasizing the importance of having an empty, unobstructed environment for ensuring safety. The remaining topics share similar importance following topics five and six, as they have an even distribution of topic weights within the LDA topic model. These topics further emphasize the absence of major safety concerns within the MR environment, with minor issues such as eye strain.

Table 6).

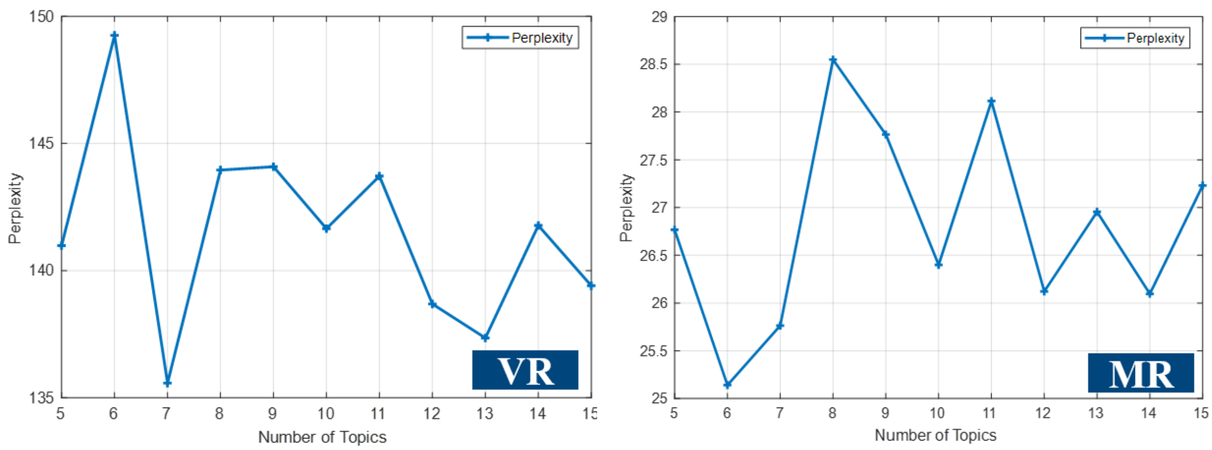

Figure 14. Perplexity Models generated for Q4.2

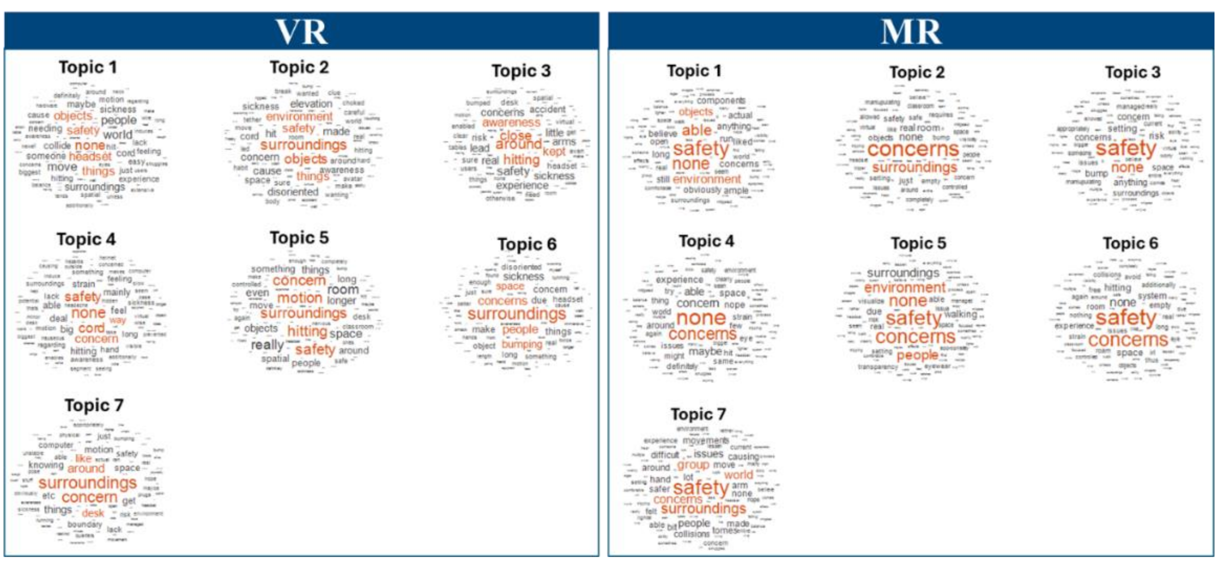

Figure 15. Generated world clouds for the two datasets (a) VR and (b) MR for Q4.2

LDA topic model for the (a) VR dataset:

The results of the LDA topic model generated for the VR dataset indicate that the topics are evenly distributed and exhibit almost the same importance. Topic five has the highest topic weight, followed by topic seven, making these two topics the most prominent topics. The topic themes assigned for topic five exhibit safety concerns related to the room space in the VR environment, emphasizing the importance of spatial awareness and freedom of movement. The theme of topic seven reveals physical risks, such as collisions with desks and computers despite virtual boundaries, showing challenges in maintaining physical safety during VR experiences. The remaining topics address other safety concerns associated with VR settings, including collisions with surrounding objects, spatial awareness issues, and the limitations of virtual boundaries in ensuring user safety.

LDA topic model for the (a) MR dataset:

The results of the LDA topic model generated for the MR dataset reveal that topics five and six, highlighted in light green, emerge as the dominant themes within the model due to their highest topic weights. The themes indicate that students perceived the MR environment as safe without observing safety concerns or risks. For instance, topic five is pivoted on the absence of safety concerns, indicating that the nature of the MR environment and the ability to manage the physical world adds no safety concerns. Topic six also emphasizes the lack of safety concerns when the surrounding environment is empty, emphasizing the importance of having an empty, unobstructed environment for ensuring safety. The remaining topics share similar importance following topics five and six, as they have an even distribution of topic weights within the LDA topic model. These topics further emphasize the absence of major safety concerns within the MR environment, with minor issues such as eye strain.

Table 6. Topics generated using the LDA Topic Model for Q4.2

LDA Topic Model for Users' Responses to Q3.2 in post-survey Set 2: ***Are there any user safety concerns associated with the two settings? Please explain for each (a) VR and (b) MR***			
(a) For VR			
Topic #	***Topic Weight***	***Top 20 Topic Words or less***	***Topic Theme***
1	14.9 %	VR, headset, safety, things, objects, move, people, surroundings, collide, cord, sickness, maybe, needing, someone, hitting, hit, easy, lack, experience	The cord with the VR headset causes colliding and hits the surrounding objects, causing motion sickness
2	14.1 %	Surroundings, objects, safety, things, hit, cause, elevation, made, concern, awareness, space, sickness, cord, make, hitting, real	The cord causes the user to hit the surrounding objects in the real world, adding safety concern
3	12.8 %	around, hitting, close, awareness, kept, safety, concerns, experience, lead, little, sickness, real, risk, accident, desk, headset, sure, users, things	Accidents like hitting the desk leading to motion sickness
4	11.8 %	none, cord, safety, concern, way, feel, big, deal, strain, mainly, able, hitting, feeling, hand, lack, something, motion, surroundings, regarding	Hitting the surroundings because of the short cord.
5	16.8 %	surroundings, hitting, motion, safety, concern, really, room, space, objects, cord, things, longer, spatial, move, around, long, people, desk, safe	Room space and long cords are needed for safety
6	14.2 %	surroundings, people, concerns, sickness, due, concern, make, things, headset, object, long, disoriented, just, something, real, enough, twice, better, bumping, space	Concerns related to having enough space to avoid bumping with objects and people within the real surroundings

7	15.3 %	surroundings, concern, around, like, virtual, desk, things, motion, knowing, space, get, boundary, safety, computer, just, lack, risk, able, physical, bumping	Physical risk related to bumping desk and computer despite the enabled virtual boundary
(b) For MR			
1	12.12 %	safety, none, able, environment, objects, believe, run, long, obviously, liked, actual, still, components, open, world, real, surroundings	None of the safety concerns as the real surrounding environment in the real world is open
2	13.93 %	concerns, surroundings, none, real, room, objects, just, safety, bump, empty, requires, safe, setting, around, classroom, virtual, space, completely, concern, controlled	No concerns, as the surrounding space is empty from real objects.
3	15.87 %	Safety, none, setting, risk, anything, concerns, concern, bump, surroundings, space, issues, managed, appropriately, current, manipulating, someone, worry, allowed	None of the risk safety concerns
4	12.45 %	none, concerns, concern, able, maybe, space, experience, around, nope, strain, world, issues, eye, hit, thing, same, few, try, definitely, might	None of the concerns: Only few issues like eye strain
5	18.36 %	safety, concerns, none, environment, people, surroundings, walking, due, real, able, setting, visualize, eyewear, transparency, issue, risk, space, managed, appropriately, seem	No safety concerns or risks, where the surrounding environment is managed
6	17.42 %	safety, concerns, none, hitting, space, system, room, experience, empty, real, long, avoid, additionally, thus, again, room, free, collisions, strain	None of the safety concerns as the space is empty
7	9.84 %	safety, surroundings, group, concerns, world, people, issues, collisions, none, around, hand, movements, causing, move, times, arm, difficult, lot, safer, made	The surroundings were safe

6. Discussion and Recommendations

The overall results, supported by existing literature, lead to the conclusion that MR is the best XR environment for manufacturing training. Regarding visualization and image fidelity, the findings from Q1 of the post-survey demonstrate that MR environments have advantages over VR. Higher mean scores and user preferences indicate that MR's holographic features, such as spatial mapping, anchoring, and object augmentation, enable more accurate interaction with virtual objects in the physical environment. This enhances UI and the replication of real-world systems. These findings align with prior research emphasizing MR's advantages in improving spatial awareness and system visualization [14], [27].

From a discomfort and adaptability perspective, Q3 results from the post-survey reveal that MR environments significantly reduce discomfort compared to VR. About 94% of students reported low to very low levels of discomfort in MR, while nearly half of them experienced high levels of discomfort in VR, primarily due to motion sickness and eyestrain. This finding is also supported by previous studies linking VR-induced discomfort to the absence of physical reference points and the misalignment of physical and virtual movements [20], [36]. Additionally, despite the fact that more students were unfamiliar with MR (52%) than VR (29%) prior to participating in the study, MR demonstrated a higher adaptability rate, with 83% of participants reporting high or very high ease in adjusting to the MR environment. This is supported by the literature suggesting that MR interfaces are intuitive and user-friendly, even for beginners [21].

From a user's safety perspective, findings from Q4 in the post-survey indicate that MR environments pose fewer safety concerns than VR. In VR, challenges included collisions with objects, spatial disorientation, and motion sickness due to limited spatial awareness and heavy headsets. These results align with studies that highlight VR's limitations in managing spatial awareness, leading to safety risks [35]. Conversely, MR environments showed minimal safety concerns, as their reliance on real-world surroundings enhances spatial context and minimizes risks, aligning with our previous study [59]. The ability to integrate physical and virtual elements makes MR safer, particularly for collaborative and multi-user tasks in manufacturing training.

The findings of this study provide answers to RQ1, demonstrating UX's impact in the XR environment on students' learning outcomes. For instance, MR was found to outperform VR in visualization and system replication, with 71% of participants selecting it as the more effective environment for visualizing internal structures and interacting with virtual assets. Its holographic features enhanced students' understanding of complex manufacturing systems and their ability to perform assembly tasks. Conversely, VR's fully immersive experience was limited by issues such as motion sickness, disorientation, and lower adaptability. Nearly half of the students reported high discomfort levels in VR, and only 51% adapted quickly to its environment, compared to 83% in MR. These findings show the impact of comfort and adaptability on training effectiveness, revealing that any user discomfort or difficulty navigating an interface will distract students from learning objectives, reducing the overall efficacy of the training experience. The findings also provide answers to RQ2, confirming that MR environments are preferred over VR environments for manufacturing training. MR's ability to combine visualization features, reduced discomfort, high adaptability, and enhanced safety makes it the optimal choice for creating effective and engaging training modules in manufacturing education.

7. Conclusion

With the rapid pace of technological advancements and the rise of Industry 4.0, incorporating advanced manufacturing training programs, such as XR training modules, is essential to bridge the gap between theoretical knowledge and practical application. This study presented a comparative research study to evaluate VR and MR manufacturing training environments, focusing on their features, functionalities, and limitations to identify the best environment for manufacturing education. Two XR environments (VR and MR) were developed with interactive training modules that focus on the assembly of a hydrostatic mechanical bike. The XR environments were tested with 95 undergraduate students, where qualitative and quantitative assessment tools, including pre- and post-survey questionnaires, were designed and validated by a research review board. All participants completed the pre-survey, engaged with the VR and MR environments while performing the assigned manufacturing assembly tasks, and then completed the post-survey. Statistical analysis and NLP (LDA topic modeling) were utilized to evaluate the collected data. The results revealed the transformative potential of MR environments for manufacturing training, demonstrating their advantage over VR in providing a safe, intuitive, and effective platform for skill development. Specifically, the MR environments were shown to be more effective in simulating real-world applications, thus preparing students for the demands of Industry 4.0. Future research will explore multi-user interactions in MR settings and address hardware limitations to enhance their scalability and applicability across diverse training scenarios.

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