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Abstract:

Mixed reality technologies have the potential to provide students with an effective learning experience by bridging the gap between digital and physical world. Mixed reality enables the user to see their real-world surroundings with virtual features overlayed on top to create a digitally enhanced experience. As we strategically move towards large-scale integration of mixed reality technologies to maximize the learning affordances in the future, there is a need to understand the drivers of and barriers to students' learning in a mixed reality environment. We present in this paper a multi-site case study to evaluate the feedback from 223 students on their learning experiences after using Microsoft HoloLens, a mixed reality device, in their classroom. While we found that interactivity, immersion, and presence are the main drivers, the key barriers identified were difficulty using the device, accessibility issues, and the lack of flexibility. Affordances and fatigue are the two themes that evolved in this study. We recommend three design principles that will contribute towards designing mixed reality technologies to effectively build new embodied learning environments.

Keywords: Mixed Reality, Flow Theory, Design Science Research.

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1 Introduction

> *"When you change the way you see the world, you change the world you see."*
>
> *(Satya Nadella, CEO Microsoft)*

Mixed reality has recently been a subject of great interest for both industry and academia. Mixed reality can change the way one sees the world, with the real world enhanced by an overlay of computer graphics-based interaction (Milgram & Kishino, 1994). The user can view the mixed reality world through a handheld or head-mounted device by layering illustrations on the surrounding environment (Harborth, 2017). Microsoft HoloLens is an example of a mixed reality device.

Mixed reality was first introduced as a training tool for airline and air force pilots during the 1990s (Caudell & Mizell, 1992). Mixed reality and related technologies offer many advantages when used in educational settings (Gasques et al., 2021; Leonard & Fitzgerald, 2018). First, it is possible to visualize and interact with complex and abstract concepts in an authentic setting. For example, Billinghurst (2002) and Leonard and Fitzgerald (2018) explain how users can move around three-dimensional virtual images to improve their learning experience. Jee, Lim, Youn, and Lee (2014) demonstrate that academic achievement using immersive learning content is higher than that using text-based content. Tang et al. (2020) evaluate the effectiveness of learning design with mixed reality in higher education and demonstrate improved capacity in model visualization. Second, mixed reality promotes seamless interaction and collaboration. For example, Martin et al. (2020) found that the deployment of mixed reality devices helped the delivery of remote care in COVID-19 hospital environments. Immersive surgical mentoring with mixed reality is promising as it facilitates untrained medical surgeons to respond to emergencies and to perform surgeries with guidance from remote experts (Gasques et al., 2021). The benefits of using HoloLens in medical and engineering fields have been established in the literature (Park, Bokijonov, & Choi, 2021). Previous studies found that the interaction of learners with the learning content in the form of gestures or movements positively influenced learners' education (Bailenson, 2017; Bailenson et al., 2008; Johnson-Glenberg, 2018).

While mixed reality is used in various fields and demonstrates significant potential, its limitations are evident. Although mixed reality demonstrates immense potential for education and business alike, barriers to the adoption of technology include the cost of devices, technical limitations, and users' proficiency (Gasques et al., 2021). The device weight while mounted on a person's head and using it, the range of time that one can reasonably use a mountable device for, the adaptability of the device based on the location, and the mobility of the user while using the device hinder the adoption of mixed reality. Further, the high cost of mixed reality equipment means that its use is cost-prohibitive. Therefore, the application of mixed reality devices in education is challenging. Limited studies have examined how the affordances of mixed reality learning environments, such as the sense of presence, gesture, and manipulation (Johnson-Glenberg, 2018), would affect the learning experiences of students. Further, studies that outline design principles for using mixed reality in IT education and the extent of an embodiment provided by mixed reality learning environments for students of diverse age groups are sparse. Hence, to address this research gap, we need to understand the positive and negative experiences students face during their learning in a mixed reality environment. Addressing this research gap is even more significant as we strategically plan for large-scale integration of technology to maximize the learning affordances in a mixed reality learning environment.

The mixed, augmented, and virtual reality market is growing rapidly and is projected to be worth US$116.88 billion by 2025 (Business Wire, September, 2021). The COVID-19 pandemic has led to a rapid acceleration in the deployment of new digital technologies to promote physical and mental wellbeing during lockdowns and to improve the accessibility of healthcare, business, and education services. As mixed reality is a direct interface to the real world, it is likely that traditional methods of teaching, delivering lectures, and tutoring students will change in the "new normal." According to Pappas and Giannakos (2021), learning designs must be revised, especially after a pandemic, and there is a need to build on the potential that today's advanced technology can deliver. Fueled by the development of mixed reality environments and the rise in remote learning due to COVID-19, there is an immense need to address the research gap and understand students' learning experiences in a mixed reality environment. This can be accomplished by examining the drivers of and barriers to students' learning in a mixed reality environment. Thus, this study aims to answer the following research questions:

RQ1: What are the factors that influence students' learning experience in a mixed reality environment?

RQ2: How can we design a mixed reality learning environment to enhance students' learning experience?

Following design science research guidelines (Hevner, 2007), this study uses flow theory (Csikszentmihalyi, 1990) to understand the drivers and barriers of students' learning in a mixed reality environment. A multi-site case study is used to evaluate 223 students from three different classes. A questionnaire is used to collect and evaluate feedback from 73 high school students, 20 postgraduate students, and 130 undergraduate students after they used Microsoft HoloLens, a mixed reality device, in their classroom. This study highlights the drivers and barriers by thematically analyzing evaluation feedback from students. The students' learning experience and the knowledge embodied in the flow antecedents, flow experience, and flow consequences are highlighted as drivers of using a mixed reality environment for learning. The accessibility and usability issues faced by students are emphasized as barriers to achieving a successful mixed reality environment for learning. The study concludes with recommendations for decision-makers in educational institutions to integrate mixed reality in their classroom by proposing design principles to enhance students' learning experience.

2 Literature Review

This section discusses related work and the theoretical foundations of the main areas of this research.

2.1 Mixed Reality

Mixed reality is a technology that overlays computer graphics over the real world and facilitates various modalities of interaction (Milgram & Kishino, 1994). A user can view the real world through a handheld or head-mounted device by layering graphic digital information on the surrounding environment (Harborth, 2017). According to Azuma et al. (2001, pp. 34) a mixed reality system has the following properties: it combines real and virtual objects in a real environment; runs interactively, in real time; and aligns real and virtual objects with each other. Mixed reality is an attempt to reach out to the reality–virtuality continuum (Milgram & Kishino, 1994). It is important to distinguish between the three related technologies termed virtual reality, augmented reality, and mixed reality:

- Virtual reality (VR) immerses users in a fully artificial digital environment (Park, 2021; Tokareva, 2018). Using a headset, users interact with an entirely computer-generated environment. Oculus Quest is an example of a VR device developed by Oculus, a division of Facebook. It is a standalone device with a headset and controller to run games and other applications. Google Earth VR is a virtual reality version of Google Earth that allows users to navigate using VR controllers. Users wearing a VR headset to view VR applications cannot view their surroundings in the real world. While users watch 360-degree videos or play VR games, they are entirely immersed in the virtual environment.
- Augmented reality (AR) overlays virtual objects in the real-world environment and uses devices like a smartphone to overlay graphics onto the physical world (Park, 2021; Tokareva, 2018). In an AR environment, the users' view of the real world will be augmented by computer-generated sensory inputs, such as sound, video, graphics or GPS data. For example, Niantic Labs' Pokémon Go is an example of an AR application on a mobile device. It adds digital content (images or text) to real-time images captured by users' cameras. IKEA Place is another example of an AR application that lets you virtually place 3D models of digital furniture into your room. Using your mobile phone camera, you can take a photo of your empty room and then augment it with a digital version of the furniture to find the most suitable match.
- Mixed reality (MR) is an advancement of AR. Mixed reality not only overlays but anchors virtual holograms in the real world by creating a hybrid environment of the real world and virtual objects. Holograms are virtual objects made of light and sound that the user can precisely place in a real-world environment to enable a three-dimensional interaction with the object. Microsoft HoloLens, a mixed reality device, is a head-mounted smart glass developed and manufactured by Microsoft. It uses holographic technology to generate augmented visuals (Hoffman, 2016). Holographic technology records the light reflected from an object and projects holographic objects as a three-dimensional image. When compared to VR and AR devices, an mixed reality device like HoloLens has advanced

features like stereoscopic 3D optical head-mounted display, gaze tracking, spatial mapping, hand gesture navigation, advanced voice, commands, and spatial sound. HoloTour is an example of a holographic application that provides an immersive travel experience using a mixed reality device like Microsoft HoloLens. HoloTour offers a 360-degree video, enriched with spatial sound and holographic scenery, to walk around and view historical cities like Rome. HoloStudio allows users to develop and design 3D models using holographic tools. HoloChemistry contains a 3D molecule builder and the periodic table to help students learn chemistry. To summarize, in a mixed reality environment, users can view the real world embedded with digital holograms and interact with digital elements. This makes mixed reality a perfect learning environment to test the experiences of learners with respect to profound affordances, such as the sense of presence, gesture, and manipulation (Johnson-Glenberg, 2018).

Interest in the use of mixed reality is growing and reflects a broader consumer interest. A promising area in mixed reality research is visualizing data with immersive analytics (Bernard & McQuillan, 2018; Mahfoud Wegba, Li, Han, & Lu, 2018). Wohlgenannt, Simons, and Stieglitz (2020) highlight that currently, mixed reality related studies are mainly in health and education and that there is significant potential to study the design and use of mixed reality technology for the future.

The pedagogical use of mixed reality applications has been researched in various disciplines, such as health (Stretton, Cochrane, & Narayan, 2018) and education, across various levels, from secondary school (Leonard & Fitzgerald, 2018) to university (John & Kurian, 2019). There are several implications as detailed in this section. First, using mixed reality in the learning design is valuable in that it provides an exceptional student experience by helping students to see the unseen. Moro et al. (2020) used HoloLens to demonstrate mixed reality as an effective delivery mode to enhance learning. Cascales, Pérez-López, and Contero (2013) implemented AR to teach natural sciences to preschoolers. Their observation results showed a positive effect on a group of students who used AR materials over traditional materials. However, few studies use MR devices, such as HoloLens, to facilitate embodied learning with immersive interaction. Second, studies have also demonstrated that using mixed reality has improved student interaction and engagement. Lindgren, Tscholl, Wang, and Johnson (2016) examine the effects of new interactions on the conceptual understanding of students and the engagement involved in learning about science. They use Meteor, an interactive stimulation of planetary astronomy that is projected onto a floor surface. The study found that the whole-body activity leads to significant learning gains, higher levels of engagement, and more positive attitudes toward science. An interactive and immersive surgical mentoring by experts from a remote location helped novice surgeons perform surgical procedures during an emergency (Gasques et al., 2021). Finally, a comprehensive review of the current state of the use of mixed reality in health by Stretton et al. (2018) revealed that the pedagogical effect of engagement on higher-order clinical reasoning remains a challenge for future studies. Gasques et al. (2021) also highlighted the technological limitations in remote assistance for surgical telemonitoring. A detailed and systematic literature review of mixed reality highlighted the importance of future mixed reality technology to be developed and improved based on the findings and insights from the information systems (IS) field (Harborth, 2017). Further, limited studies have examined the affordances of learning (i.e. sense of presence, gesture, and manipulation) in a mixed reality environment (Johnson-Glenberg, 2018). Given the maturity and availability of mixed reality technology, the adoption of mixed reality to support the education process is a realistic application scenario. Hence, the aim of this study is to design, test, and evaluate a mixed reality learning environment to examine the learning experiences of a diverse age group of students and, thus, identify the drivers of and barriers to students' learning experience using a design science research (DSR) framework.

2.2 Design Science Research

DSR provides a framework of design principles that indicate how to construct and execute a task to achieve a goal. This framework is important as a means of accumulating knowledge and acting on it using complex artifacts in a real-world scenario (Gregor, Chandra Kruse, & Seidel, 2020). DSR involves the creation of an artifact to improve the current state of practice and contributes to existing research knowledge as a form of design theory (Baskerville, Baiyere, Gregor, Hevner, & Rossi, 2018). As Simon (2019) explains, design science is the science of artificial objects designed to meet certain criteria. The artifacts are man-made and include models, methods, constructs, instantiations, and design theories (Gregor & Hevner, 2013). The analysis of the artifacts' use and performance, which leads to reflection and abstraction, is the core component of DSR.

Using the DSR framework, Amrollahi and McBride (2019) explore how bubbles can be filtered in social media discussions. John, Chua, Goh, and Wickramasinghe (2016) use design science to develop a graph-based cluster analysis approach to identify similar questions posed on social media. Barafort, Shrestha, Cortina, and Renault (2018) use a well-articulated approach with the creation of a Software as a Service (SaaS) tool to support a standard framework. Design science has also been used to evaluate issues related to the use of data. Kao et al. (2016) follow a DSR approach to design and evaluate a business intelligence system for use in hospitals. Imran and Gregor (2019) show how IT mindsets influence personal innovativeness. DSR is an established approach in the field of IS. It provides a bridge between cross-disciplinary theories and techniques and a real-world business need, represented by people, organizations, and technology (Vom Brocke Winter, Hevner, & Maedche, 2020). As illustrated by Hevner et al. (2004), the relevance of the research is defined by business needs. The rigor for the research is achieved from the academic knowledge base and is reflected in the research project. A cycle of development and evaluation is the key concept of DSR.

The DSR framework is a socio-technical lens that is relevant to educational settings. Teaching is like a design science "because it uses what is known about teaching to attain the goal of student learning and uses the implementation of its designs to keep improving them" (Laurillard, 2012, p. 1). Previous studies have used the DSR methodology to build an artifact and examine the qualitative feedback provided by experts in a mixed reality environment (Nguyen, Tuunanen, Gardner, & Sheridan, 2021; Vasilevski & Birt, 2019). The three cycles of DSR (i.e., relevance cycle, rigor cycle, and design cycle) used in this study are explained in Section 3. We used the DSR methodology since it is suitable for designing, testing, and evaluating our approach to examine the learning experiences of a diverse age group of students in mixed reality environments.

2.3 Flow Theory

Flow theory describes a mental state in which an individual focuses completely on and participates in an activity (Csikszentmihalyi, 1990). It deals with intrinsic motivation and immersion while being involved in an activity. Flow theory describes the difference between anxiety and boredom during an activity. Eight dimensions that support the flow experience are achievable tasks, concentration, clear goals, feedback, effortless involvement, control over actions, the disappearance of concern for self, and loss of sense in time (Csikszentmihalyi, 1993).

Researchers have frequently applied flow theory in IS research, such as to investigate how the virtual world influences brand equity (e.g., Nah, Eschenbrenner, Zeng, Telaprolu, & Sepehr, 2014), to identify the effect of product purchase preferences on different types of users (Liu, Li, & Santhanam, 2013), and to investigate how intrinsic motivation can be achieved with information technology (Gerow, Ayyagari, Thatcher, & Roth, 2013). Several studies have revealed flow experience to be an independent positive predictor of learning, such as when playing computer games (Murphy, Smith, & Hancock, 2008) and in computer performance (Vollmeyer & Imhof, 2007). In previous studies, flow-based explanations have been in the context of human-computer interaction (Huang, 2003), intention to use the technology (Agarwal & Karahanna, 2000), reuse of a technology (Koufaris, 2002), increased learning (Skadberg & Kimmel, 2004), e-learning success (Guru & Nah, 2001), intention to play online games (Hsu & Lu, 2004), satisfaction with websites (Deng, Turner, Gehling, & Prince, 2010), loyalty to websites (Siekpe, 2005), and online purchase intentions (Hausman & Siekpe, 2009).

Flow experience in a computer-mediated environment has been demonstrated based on various constructs. Control and challenge were identified to predict flow (Csikszentmihalyi, 1993). Ease of use was identified by Trevino and Webster (1992), while Ghani and Deshpande (1994) highlighted skills and challenges to the constructs of flow antecedents. Novak, Hoffman, and Yung (1998) propose that enjoyment, concentration, control, attention focus, curiosity, and intrinsic interest define flow, as illustrated in an eight-channel flow model. Further, Novak, Hoffman, and Yung (2000) identified 13 constructs: challenges, skills, focused attention, control, positive affect, involvement, interactivity, playfulness, time distortion, arousal, exploratory behavior, optimum stimulation level, and telepresence. Finneran and Zhang (2005) provide a comprehensive comparison of various models and constructs within the three phases of the flow of learning. In addition to the constructs of flow, the engagement experienced by users is mainly influenced by its interactivity level, as explained by Mahfouz, Joonas, and Opara (2020). Table 1 summarizes the list of constructs identified by Finneran and Zhang (2005), Ghani (1995), Novak (2000), and Mahfouz et al. (2020).

Table 1. Constructs of Flow Model Adapted from Previous Studies (Chen, 2000; Finneran & Zhang, 2005; Ghani, 1995; Mahfouz et al., 2020; Novak, 2000)

Flow Antecedents	Flow Experience	Flow Consequences
• Skills • Challenge • Control • Telepresence • Interactivity • Cognitive spontaneity • Vividness • Focused attention • Involvement • Immediate feedback • Action awareness • Speed • Ease of use	• Enjoyment • Concentration • Time distortion • Loss of self-consciousness • Telepresence	• Focus on process • Learning • Creativity • Perceived control • Positive experience • Exploratory mindset • Change of attitude

However, Finneran and Zhang (2005) highlight the inconsistency in some studies using flow theory and the need to identify and differentiate the person experiencing flow, the tasks, and the type of artifact that assists the user in accomplishing tasks. The need to identify and differentiate the person experiencing the flow, the tasks, and the type of artifact are particularly important. In this study, the artifact is the mixed reality device that assists students in learning. As stated by Mahfouz et al. (2020), mixed reality devices will fall under the fourth quadrant of the flow model of human-to-machine interactivity because users are immersed in the activity while using mixed reality devices. Finneran and Zhang (2005) also suggest the use of qualitative methodologies to measure the experience of the users, mainly because enabling respondents to use their own words to describe their experiences can ensure validity and uncover deeper aspects of the flow model within a computer-mediated environment (Novak, Hoffman, & Duhachek, 2003). Further, gestures required by the mixed reality device enhance motor planning because gesturers require mental stimulation. Adding gestures to engage in a highly immersive platform in a three-dimensional view of holograms will enhance embodied learning (Johnson-Glenberg, 2017). Hence, recognizing the knowledge embodied by measuring the constructs of flow theory will help us understand the embodied learning experience and the extent of affordances in learning in a mixed reality environment. Thus, research rigor is achieved by identifying drivers and barriers that influence the flow of the learning experience for students in a mixed reality learning environment. Section 3 provides a detailed overview of the methodology.

3 Methodology

As detailed in the DSR framework (Hevner et al., 2004), the three cycles of design science used for this study are discussed in this section.

The relevance cycle bridges the contextual environment of the research project with the design science activities (Hevner, 2007). There are two elements in this project that fit within the relevance cycle. First, the initial observation triggered the original research question. There is a need to identify the drivers of and barriers to students' learning in a mixed reality learning environment. Second, we gauge and articulate learning experiences by analyzing the qualitative questionnaire answered by students.

The rigor cycle connects activities with the knowledge base of scientific foundations, experience, and expertise that inform the research project (Hevner, 2007). This study identifies various drivers and barriers from previous IS literature that relate to the flow of learning experience in innovative computer-supported learning environments. This adds to the body of knowledge by contributing design principles for mixed reality learning environments.

The design cycle iterates between the core activities of building and evaluating the design artifacts and the process of the research (Hevner, 2007). From the insights, the scope of this study is not to design a mixed reality device or an application. Instead, the scope is to design the flow of learning by using a mixed reality device in the classroom and to trial and evaluate the drivers and barriers of students' learning based on the students' feedback. The design principles derived from the findings of this study will contribute toward mixed reality designs for education in the future.

Figure 1. A Set of Photos Taken while Students Used HoloLens in Their Classroom

3.1 Participants

This study was developed as a multi-site case study. A total of 223 students from three different class levels participated in the study (Figure 1). Participants' details are provided in Table 2. The students were informed in advance regarding the experiment. Participation was on a voluntary basis in their classroom environment, and the data was collected with their consent. Qualitative feedback provided by this diverse age group of learners was analyzed to ensure the validity of our study.

Table 2. Participant Information

Number of Students	Class Level	Subject
73	High School	Science
20	Graduate	Information Systems in Organizations
130	Undergraduate	Management Information Systems

3.2 Pedagogical Design

The pedagogical design and the research settings used for the three case studies are detailed in this section. In this study, we approach learning in a mixed reality environment as a form of experiential learning (Yang Chen, Zheng, & Hwang, 2021).

The pedagogical design for this form of experiential learning consisted of the following phases. The first phase involved determining how to orient the students and designing the tasks related to the learning activity so that the students would experience the mixed reality learning environment and accomplish the learning objective for the session. The second phase consisted of developing an orientation to HoloLens. This included a video of how HoloLens works so that students would have an in-depth understanding of the technology behind mixed reality. The third phase involved developing alternative pathways to complete the task as the use of the mixed reality device was voluntary. On average, there were approximately 20 students in each class, and they formed groups of four or five. The fourth phase involved developing measures and protocols to maintain health and safety requirements, including sanitizing the device each time it was used. The processes followed in carrying out the research were documented and tested. Ethics approval was received before we conducted the project.

The process of designing the task was mainly focused on helping students relate their learning experience to their assessment tasks and to achieve the learning outcomes. For example, undergraduate students were asked to design and apply the concepts in Porter's five forces model to the tourism industry using the HoloTour application. They had to take a walk through the HoloTour application and share their experience with their group. Finally, they needed to prepare a presentation explaining how each of the five forces affected the business processes in tourism. The tasks were created with a focus on nurturing a culture of innovation through embedding experimentation and entrepreneurial pedagogical practices into the learning environment. The mixed reality applications used were HoloTour, HoloStudio, and HoloChemistry. The RoboRaid gaming application and Galaxy Explorer were the other options that they had the choice to explore. Students also had options to use the device or pursue alternative tasks to accomplish the learning objectives.

Stages	Detailed Steps
1. HoloLens Orientation	• Watch HoloLens Video presented • Watch the demonstration
2. Introduction to the task	• Introduce the question • How to work in groups with HoloLens • How to save the file
3. Group Formation	• Form the groups of five students
4. First experience with HoloLens	• Take 10 minutes to experience HoloLens and familiarize with the controls and the device • Debrief what you see to your group members • Use hand gesture navigation and voice commands to familiarize with the device
5. Design with HoloLens	• Choose the question to work as a team • Start designing and answering the question given • Save your work
6. Present	• Present your findings and answers to the class
7. Questionnaire	• Participate in the survey • Sign your consent
8. Summary	• Conclude the session

Figure 2 Procedure Used to Conduct the Experiment

3.3 Procedure

A preparatory demonstration session for the teaching team was conducted to understand and gain experience to manage the mixed reality learning environment using HoloLens. To meet relevant safety and quality regulations, students were provided with wipes and tissues to sanitize the devices before they exchanged the device in their teams. The mixed reality environment helped students relate this experience in their assessment tasks. The task was designed to integrate with the learning activity to achieve the learning outcome. However, the outcome of the task was not formally assessed. Participation in this project was completely voluntary. A questionnaire was used to collect and evaluate the feedback from 73 high school students, 20 postgraduate students, and 130 undergraduate students after they used the Microsoft HoloLens mixed reality device in their classroom to complete the learning task. The procedure used to coordinate the class for undergraduate students is presented in Figure 2. Similar procedures were used for graduate and high school students.

3.4 Data Collection and Analysis

The students were presented with a questionnaire to answer three open-ended questions after they had completed the learning task in a mixed reality environment. This study focused on the two open-ended questions to qualitatively analyze and understand the key themes and identify the drivers and barriers experienced by students. The three open-ended questions are as follows:

Q1: What was your best experience using the mixed reality application?

Q2: What was your worst experience using the mixed reality application?

Q3: What would you like to see changed or added to this application?

Previous research has used content analysis to understand themes related to antecedents, experience, and consequences of flow. The data was analyzed based on the steps recommended for thematic analysis (Braun & Clarke, 2012). Data was coded based on the constructs of the flow model (Table 1). Data analysis resulted in the following constructs: interactivity, immersion, presence, innovativeness, ease of use, accessibility, flexibility, reliability, and response time (Al-Busaidi, 2012; Costello, Donnellan, & Curley, 2008; Davis 1989; Shiau & George, 2014; Steuer, 1995; Witmer & Singer, 1998; Vaezi, Mills, & Chin, 2019). Among the responses, 9.5% were not coded because the students did not provide an answer. The set was coded independently by two researchers. The inter-rater reliability between the coders was above 82%. Inter-coder reliability was high, particularly for constructs where the answers were very clear and concise. For example, "new" and "it's innovative" were coded as innovativeness. The definition of the constructs used for data analysis with respect to the mixed reality learning environment are listed below (Tables 3 and 4).

- **Interactivity:** According to Steuer (1995), interactivity is defined as "the degree to which users of a medium can influence the form or content of the mediated environment." It is a stimulus-driven variable and measures the extent to which users can participate in modifying the content of a mediated environment in real time. Interactivity is an important measure to evaluate the student's learning experience in a mixed reality environment due to the tangible user interface and spatial recognition provided by Microsoft HoloLens. Interactivity is identified as a construct of flow antecedent.
- **Immersion:** As stated by Witmer and Singer (1998), immersion is defined as "a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences." As a mixed reality environment offers a greater sense of immersion, it will produce a higher level of telepresence. Immersion measures the perception of natural modes of interaction and control in the mixed reality environment and the degree to which students feel immersed in the learning environment created by the mixed reality application. Immersion is a user experience variable that influences the user's presence as a construct of flow antecedent and flow experience (Steuer, 1995; Witmer & Singer, 1998).
- **Presence:** Presence is defined as "as the sense of being in an environment" (Steuer, 1995). When the activity involved is mediated by a technology, the user is forced to perceive two separate environments simultaneously. Telepresence is used to describe the precedence of the technology experience in favor of the real-world experience. Although interactivity and immersion are important constructs to experience the presence in an environment, individual differences and abilities may enhance or detract from the experience of presence or telepresence in a mixed reality environment. Hence, presence is an important measure with respect to mixed reality devices because the overlaying of computer graphics-based over the real world creates a visualization experience that contributes to a sense of being. Presence is a construct of flow antecedent as well as flow experience (Table 1).
- **Innovativeness:** The introduction of something new is defined as "innovation." Adoption of something new occurs when a user integrates an innovation into their life (Straub, 2009). From the perspective of flow theory (Csikszentmihalyi, 1988), innovativeness corresponds with the balance of challenges and skills in an activity. Challenges and skills are the antecedent constructs within the flow model (Finneran & Zhang, 2005). Innovativeness contributes to enjoyment as a flow experience and creativity as a flow consequence (Costello, Donnellan, & Curley, 2013).

- **Ease of use:** Several studies have found a significant negative effect of users' computer anxiety and technology experience on their perceived ease of use of e-learning (Al-Busaidi, 2012). Davis (1989) defines ease of use as "the degree to which a person believes that using a particular system would be free from effort." Perceived ease of use is a well-researched construct in the technology acceptance model. It is important to understand ease of use as students experience the use of a mixed reality device for learning. The success or failure of a device depends on how well the user likes the device, how easy it is to use, and its effectiveness. Technology experience or the extent of users' exposure to a system is also a factor that influences the ease of use of a system (Al-Busaidi, 2012). When using mixed reality devices to learn new concepts or complete a task, users need to be free from extra effort, and, hence, ease of use is an important construct to measure the flow antecedents (Table 1).
- **Accessibility:** Accessibility is the practice of making devices or services accessible to people. As illustrated by Zhao et al. (2019), there is a need to make 3D virtual spaces more accessible when the head-mounted device enables the visualization and manipulation of 3D images. The accessibility construct is important with respect to mixed reality technologies to ensure an inclusive experience. Supporting people with glasses, low vision, or visual impairments is a key component to measure the students' learning experience in a mixed reality environment. Not only visual impairments but also other physical and mental limitations play a significant role in the accessibility of a device. As Cocosila and Archer (2016) highlight, the level of stress and the extent to which a user experiences emotional tension while using a system are key factors relating to the accessibility of a device.
- **Flexibility:** Vaezi, Mills, and Chin (2019) define flexibility as the extent to which a system adapts to changing requirements, which contributes to user satisfaction. Flexibility with respect to time, location, and learning is a major factor for the learner's acceptance of a system (Arbaugh, 2000). Al-Busaidi (2012) discusses flexibility and its role in blended learning. From the perspective of students' use of mixed reality devices for learning, flexibility will help to measure the extent to which students are able to adapt the device and its interface to satisfy their needs (Al-Busaidi, 2012; Shiau & George, 2014).
- **Reliability:** The reliability of the system is based on the consistency and dependability of the service performance and the credibility of the service provided. Reliability is described by Vaezi, Mills, and Chin (2019) as a factor that influences system satisfaction. There is a need to understand the extent to which the students find mixed reality devices reliable for their learning. Reliability is an important measure to explore, mainly because students communicate with the mixed reality devices using their voice and actions (Al-Busaidi, 2012; Vaezi et al., 2019).
- **Response Time:** As students use mixed reality devices for the tasks assigned to them, response time is important to make sure they progress through their learning smoothly. A slow response time will distract the students and demotivate them from using the application. Downward time distortion is identified as one of the challenges in flow theory (Csikszentmihalyi, 1993).

Tables 3 and 4 present the constructs classified as drivers and barriers, along with their definitions, examples, and inter-rater reliabilities. The important findings are highlighted, and recommendations are presented in Section 4.

Table 3 Definition and an Example of Drivers

Constructs	Definition	Example	References	Inter-rater reliability (%)
Interactivity	The extent to which users participate and modify artifacts in a mixed reality environment in real time.	"being able to walk around the compound I made and zoom in on it"	Steuer, 1995	86.3
Immersion	The extent to which users are inspired and absorbed in the richness of a mixed reality environment.	"engaged students who are usually disengaged!"	Steuer, 1995; Witmer & Singer, 1998	82.19
Presence	The users' subjective experience of being in a mixed reality environment over their physical location.	"being able to look at the solar system and learn about it"	Steuer, 1995; Witmer & Singer, 1998	98.63
Innovativeness	The extent to which users experience new methods or processes in a mixed reality environment.	"it's new and different"	Costello, Donnellan, & Curley, 2013	100

Table 4 Definition and an Example of Barriers

Constructs	Definition	Example	References	Inter-rater reliability (%)
Accessibility	The extent to which a system is available for users with diverse needs to access content.	"eyestrain" "It is very hard to see"	Al-Busaidi, 2012; Bradbard & Peters, 2008	81.25
Flexibility	The extent to which a user could adapt a system to fulfil individual requirements.	"the vertical field of view was so small that many apps didn't fit/were unusable without continuous adjusting"	Shiau & George, 2014; Al-Busaidi, 2012	87.50
Ease of use	The extent to which a user believes that using a system would be free from effort.	"quite hard to operate" "being an amateur, it was hard to navigate"	Davis 1989; Al-Busaidi, 2012	93.75
Reliability	The extent to which a system does function dependably.	"surface recognition and Cortana got a bit annoying when the person next to you said 'Hey Cortana', and it activated yours"	Vaezi, Mills, & Chin, 2019; Al-Busaidi, 2012	98.39
Response time	The extent to which a system carries out requests for action in a timely manner.	"the glitch—it would freeze quite a bit. Unable to move the molecules"	Vaezi, Mills, & Chin, 2019; Al-Busaidi, 2012	98.39

4 Results and Discussion

The drivers based on the three case studies followed by the barriers are presented in this section.

4.1 Drivers of the Students' Learning in a Mixed Reality Environment

The key drivers that emerged from the analysis of data were interactivity, immersion, presence, and innovativeness. Each of these constructs is explained below. Figures 3 and 4 present the percentages of the types of students whose responses were categorized across the constructs.

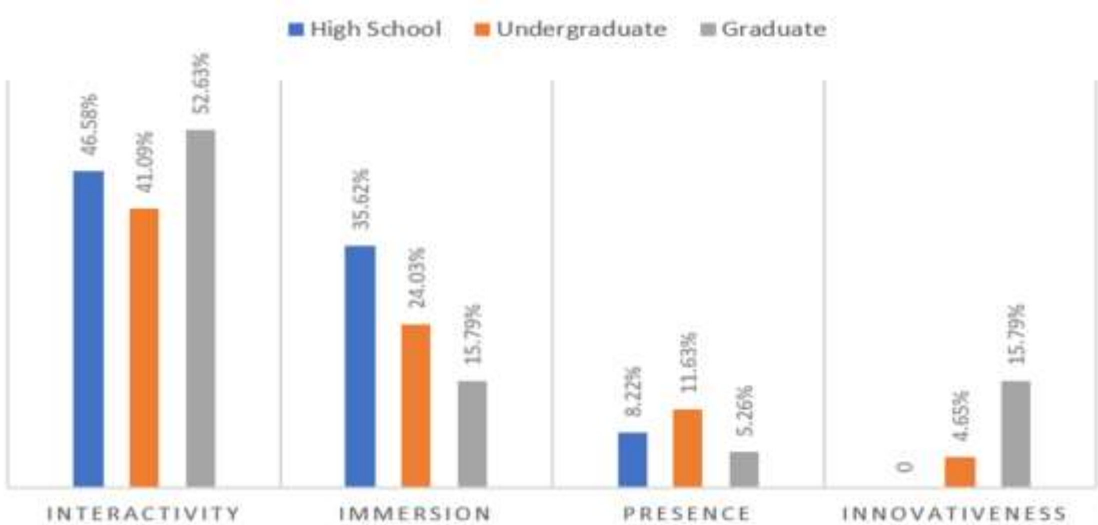

Figure 3 Drivers of Students Learning in a Mixed Reality Environment

4.1.1 Interactivity

Interactivity is defined as the extent to which users participate and modify artifacts in a mixed reality environment in real time. The characteristics of interactivity experienced by the participants include visually examining objects from different angles (i.e., a 360-degree view) and learning by interacting with objects. An example of interactivity, as stated by one student, is "the ability to move around the objects." Another characteristic is the use of hand gestures to control and manipulate objects in a real-world setting and accessing multiple objects or applications at the same time in a mixed reality environment: for example, "being able to control everything" and following an "interactive and hands-on approach." Among the different types of knowledge, interactivity reflects procedural knowledge since it includes both implicit and explicit procedures adopted by users to accomplish a learning task in a mixed reality environment. As stated in the feedback, "being able to visualize something so small and being able to manipulate it" is an example of procedural knowledge created by the interactivity of the mixed reality environment. From the perspective of flow theory (Csikszentmihalyi, 1988), interactivity, as discussed here, corresponds with perceived control, which is one of the antecedent constructs within the model (Finneran & Zhang, 2005) that contributes to enjoyment as a flow experience and process focus as a consequence. An example of enjoyment is "that it was a new way to learn and interact with learning information in a new way," and an example of process focus is "shooting the robots and using physical movements to help improve my agility." Embodied affordances of the mixed reality environment were evident in the student learning experience. Some examples are as follows: "The interactions with the real world were extremely useful and extremely interesting;" "That it was interactive, and I could move around with it;" "The ability to move around the objects;" and "Being able to walk around the compound I made and zoom in on it." These examples demonstrate embodied affordances of gesture and manipulation in the third dimension (Johnson-Glenberg, 2018).

Interactivity was found among all three case studies. A few high school students experienced a new way of learning in the mixed reality environment. For example, "it was new way to learn and interact with learning information in a new way." From the perspective of the adoption of a new technology (Davis, 1989), interactivity reflects usefulness since the mixed reality environment helped students to accomplish their learning tasks. An example of interactive learning by a school student is "learning physically not just in a book." In contrast, undergraduate students experienced a high degree of ease of use, which reflects that using a technology is free from effort in the context of its adoption. For example, one student described the technology as "fairly easy to use; you can see and learn instead of reading a book." Ease of use is also evident as one of the barriers, as highlighted later in the study. This is mainly because the findings on usefulness and ease of use could be attributed to the Generation Z participants (i.e., high school and undergraduate students). From a practitioner's perspective, this approach could be used by higher education institutions to reduce attrition rates and improve retention and completion among sophomores. Further, graduate students could reap the benefits by understanding the practical implications of mixed reality applications.

To summarize, the interactive learning experience in a mixed reality environment offered an improved three-dimensional view as well as synchronized hand controls. View and control led to embodied affordances in the mixed reality environment, which will have a long-lasting positive effect on the quality of the pedagogy and student learning experience (Johnson-Glenberg, 2018). Hence, interactive learning needs to be designed and embodied into educational spaces with a mixed reality learning environment.

4.1.2 Immersion

Immersion is defined as the extent to which users are inspired and absorbed in the richness of a mixed reality environment. The characteristics of immersion experienced by the participants include visualization of ideas, concepts, and objects. An example from the data collected is "the ability to see the bonding pairs and how they cause the structure." Another characteristic is the enjoyment and immersive experience felt by participants while learning tasks in the mixed reality environment. One student stated: "You can understand easier because it visualizes the point." Many students highlighted immersive learning experiences they had with respect to visualization, responsiveness, and engagement. For example, one student expressed that the learning experience was "new, exciting, innovative, engaging and responsive." According to another, "The visualization apps were amazing quality; the tour of Rome was good as it walked me through and talked to me." More examples that demonstrate their learning experience are as follows: "Amazing user experience. Excellent for teaching in class;" "It was visual so easy to understand;" "HoloLens could let me learn things in real feeling;" "Learning is much more interesting;" "It's easier for students to understand the knowledge;" and "Interesting, very useful, new study technique." Fun is another aspect of immersive learning experienced by students. For example, "it's super impressive and fun;" "the fun of controlling everything." In an in-depth analysis of different types of knowledge, immersion reflects teleological knowledge (Pee, Pan, & Cui, 2019) since the rationale for using a mixed reality environment is to make learning a fun and interesting experience. Another example of immersion reflecting theological knowledge is a student describing "an unusual, interesting experience." Based on the flow theory (Csikszentmihalyi, 1988), immersion corresponds with involvement, which is one of the antecedent constructs within the flow models (Finneran & Zhang, 2005). Immersion contributed to enjoyment and loss of self-consciousness as a flow experience and increased learning consequently. An example of enjoyment due to immersion is "It was just really fun," an example of loss of self-consciousness is "engaged students who are usually disengaged!" and an example of increased learning as a consequence is "You can understand easier because it visualizes the point."

On comparing the three cases, immersion was reported by all the participants. Among these participants, a few high school students experienced incredible enjoyment while completing tasks in the mixed reality learning environment. Based on previous literature, motivation to use a technology reflects enjoyment that leads to intrinsic motivation for users' intention to continue to use a new environment for accomplishing their learning tasks (Davis, 1992). In contrast, undergraduate students experienced a high degree of interactivity as well as usefulness, which is evident in this example: "It was very interactive and visualizing, certain things help to remember it better." A few of the undergraduate students felt that they could accomplish their learning tasks in a mixed reality learning environment without much effort, which reflects ease of use. Further, an undergraduate student experienced a flow state in which there was a balance between skills required and challenges involved in completing a task in the mixed reality environment. An example is: "fun, something difficult and challenging, easy to use." A few graduate students commented on the rich user experience provided in the mixed reality environment and the application of mixed reality in teaching and learning. In general, high school students experienced enjoyment; undergraduate students experienced usefulness, ease of use, and a flow state; and graduate students recommended the application of mixed reality in education due to its immersive user experience.

The immersive learning experience in the mixed reality environment highlighted not just the visualization, engagement, and fun that students experienced but how these factors improved their learning. Thus, embodiment of immersive learning into educational spaces needs to be designed with a mixed reality learning environment by improving sensorimotor engagement, gestural congruency, and sense of immersion, as suggested by Johnson-Glenberg (2018).

4.1.3 Presence

Presence is defined as the users' subjective experience of being in a mixed reality environment and their physical location. A characteristic of presence experienced by the participants is captured in how they adapt to the environment. An example of presence evidenced in the data collected is "being able to play games in the surrounding room, and the apps are in front of you." This is a classic example of how students take their presence in a mixed reality environment to experience the mixing of the real world with the virtual world. According to Slater and Wilbur (1997), presence is described as the feeling of being there. Examples that reflect the illusion of presence in the virtual world are as follows: "You can feel the place where you are not present;" "Be in a place you aren't;" "In HoloTour it was cool to be able to view a typical street setting, and the daily activities of locals in a Peruvian town;" and "You can be in Italy without paying." Presence is also aligned with the non-subjective property of the technological system. For example, "Being able to play games in the surrounding room and the apps are in front of you." Presence reflects declarative knowledge (Spiegler, 2000) since it addresses the "what" aspect of a learning task (i.e., what can be accomplished in a mixed reality environment). An example of declarative knowledge provided by a student is "visuals of the human body." According to flow theory (Csikszentmihalyi, 1988), presence, as discussed here, corresponds with telepresence, which is one of the antecedent constructs within the flow models (Finneran & Zhang, 2005). Presence contributes to loss of self-consciousness as a flow experience and exploratory mindset as a consequence. An example is "hologram—being in front of you," and an example of exploratory mindset is "the accuracy of it finding and adapting to your surroundings."

On comparing the three cases, presence was found among all the participants. Among them, high school students were able to seamlessly adapt to surroundings to accomplish learning tasks in a mixed reality environment. From the perspective of adoption of a new technology (Davis, 1989), this reflects ease of use since accomplishing learning tasks in a mixed reality environment was free from effort. In contrast, undergraduate students experienced enjoyment, usefulness, and ease of use. Enjoyment was experienced by a few undergraduate students during historical tours in the mixed reality environment. An example of enjoyment creating presence is "enjoyed touring around, found history interesting." Another example of usefulness creating presence is "what made the augmented reality worthwhile was how well it integrated with my environment and how easy it was to use." Among the graduate students, one of them commented on the ability to view different countries in a mixed reality environment. An example is "actual view of different countries, interesting." In general, high school students experienced ease of use, undergraduate students experienced enjoyment and usefulness enhancing their presence, while graduate students found the mixed reality environment interesting in the context of a virtual presence.

To an extent, presence is not under the control of the learning designer. Facilitating a mixed reality learning environment will enhance the sense of presence and will depend on the challenge in the task, skills in using the technology, prior knowledge, and motivation. An interactive and immersive learning environment will effectively enhance the presence. A higher degree of presence will correlate with higher levels of embodied learning and affordances in mixed reality learning environments (Makransky & Petersen, 2021).

4.1.4 Innovativeness

Innovativeness is defined as the extent to which users experience new methods or processes in a mixed reality environment. An example to quote from the students' feedback is: "Best way for students to learn something new." From the perspective of flow theory (Csikszentmihalyi, 1988), innovativeness, as discussed here, corresponds with the balance of challenges and skills in an activity, which is one of the antecedent constructs within the flow models (Finneran & Zhang, 2005). Innovativeness contributes to enjoyment as a flow experience and creativity as a consequence. An example of enjoyment is "it's mind-blowing," and an example of creativity is "something live, never seen before so feels like the face front of technology." Among the different types of knowledge, innovativeness reflects conditional knowledge (Pee, Pan & Cui, 2019) since it addresses the 'when' aspect of a learning task. Although the extent to which users experience new methods is evident in the interactivity, immersion, and presence, the explicit quotations related to innovativeness were relatively fewer.

On comparing the three cases, innovativeness was found only among undergraduate and graduate students. It was also least evident in comparison with other drivers. Among the participants, undergraduate students received a positive experience while accomplishing learning tasks in a mixed reality environment and felt that it provided a suitable platform for digital native learners. An example is "it's innovative and mind-blowing." The students' overwhelmingly positive experience reflects enjoyment, which is considered an intrinsic motivation for students' intention to continue to use a mixed reality environment for learning. In contrast, graduate students found the mixed reality environment new and considered it one of the best ways for students to learn new things. In general, high school students did not experience innovativeness, undergraduate students experienced enjoyment, and graduate students found the mixed reality environment new and interesting in the context of learning.

Table 5. Drivers, Type of Knowledge and Flow of Knowledge

Mixed Reality Environment		**Constructs within Flow Model**		
Drivers	**Types of Knowledge**	**Flow Antecedents**	**Flow Experience**	**Flow Consequences**
Presence	Declarative	Telepresence	Loss of self-consciousness	Exploratory mindset
Interactivity	Procedural	Perceived control	Enjoyment	Process focus
Innovativeness	Conditional	Balance of challenges and skills in the activity	Enjoyment	Creativity
Immersion	Teleological	Involvement, balance of challenges and skills in the activity	Enjoyment, Loss of Self-consciousness	Increased learning

In summary, the drivers related to user experience were found in the order of interactivity, immersion, presence, and innovativeness. The findings are compared based on the three cases to reflect the differences in the experience based on their age groups (Figure 3). Some students either left blank or answered the name of applications as "Galaxy," for example. These answers were coded as not applicable. Case 1 represents high school students, case 2 represents undergraduate students, and case 3 represents graduate students in the stream of science and technology. Table 5 summarizes the findings in terms of the drivers, the type of knowledge embodied in a mixed reality environment, and how they are related to the different phases (antecedents, experience and, consequences) within the flow model.

4.2 Barriers to the Students' Learning in a Mixed Reality Environment

The barriers identified are ease of use, flexibility, accessibility, reliability, and response time. There is also a small percentage of students who explicitly wrote that they did not experience any barriers (Figure 4).

4.2.1 Ease of Use

Ease of use has been defined as the extent to which a user believes that using a system would be free from effort (Al-Busaidi, 2012; Davis 1989). Ease of use was not experienced by some of the survey participants, and they experienced "difficulty to use" and inconvenience in a mixed reality environment. Some examples that highlight the difficulty experienced are: "operating the app was very difficult;" "sometimes was difficult to use;" "as a beginner, it was hard to use and navigate." Some students shared that they had difficulty in the initial stage, which they were able to overcome. Student comments included: "slightly difficult to use at first and requires adjust period;" "difficult to use at start but didn't experience anything major;" "being an amateur it was hard to navigate;" "the clicking motion was hard to get used to in the beginning." The negative aspects that contributed to this inconvenience include difficulty in using hand gestures and voice commands to control an object. For example, students commented that it was "hard to control with hand gestures; didn't respond to the voice commands." In addition, "it was a little difficult to get used to the hand gestures;" "it was very hard to use the controls, very temperamental;" and "the hand gestures didn't work." Multimodal effects are rich in a mixed reality environment. Auditory and haptic cues increase sensorimotor activation in embodied learning. To an extent, beginners will need time to master their control and skills. For example: "it was difficult to learn movements/actions, note: similar to using a computer for the first time;" "hard to work out for the first time;" "it can be a little hard to get used to and to use it in the most efficient way." A few students highlighted inconvenience in terms of environmental factors, such as background light and classroom settings. Examples included: "it was best used with lights off'; "this device would be better off used in classes with white walls."

Among the participants, few students had difficulty using the device. High school and graduate students reported that it was hard to use a mixed reality environment for accomplishing learning tasks, whereas undergraduate students attributed this difficulty to environmental factors. This finding (i.e., difficulty to use) corresponds with the system quality characteristics (Al-Busaidi, 2012) perceived by learners on the success of a system in blended learning. Since blended learning is widely used in institutes of higher learning and ease of use is a critical success factor for systems in blended learning, administrators must devise policies to mitigate the barriers that users face to accomplish learning outcomes in mixed reality environments. In general, among the participants, ease of use was largely not experienced by graduate students, followed by high school and undergraduate students. This finding corresponds with the relationship with the age group, their skills, and the interactivity. The younger generation found the mixed reality environment more interactive as well as appreciating ease to use, while the elder age group found it harder to use. This must be taken into consideration by academics using mixed reality learning environments for teaching in higher-level courses. Learnability and ergonomics of the systems need to be included as major components for the design of a mixed reality learning environment to facilitate an immersive learning experience.

4.2.2 Flexibility

Flexibility is defined as the extent to which a user could adapt a system to fulfil individual requirements (Al-Busaidi, 2012; Shiau & George, 2014). Lack of flexibility was experienced by the participants in the mixed reality environment with respect to adjustment gestures, menu options, navigation, and control. An example of an adjustment gesture is "sometimes the clicks didn't register." Menu options were found to be limited. For example, "the menu can be confusing." Navigation in the limited field of view was found to be challenging by the participants. An example is "the vertical field of view was so small that many apps didn't fit/were unusable without continuous adjusting." The participants also found the mixed reality environment less flexible and difficult to adapt. For example, students' comments included: "can be a little tricky to control;" "too little selection;" and "forced orientation." Students mainly experienced difficulty with spatial mapping and control in placing holographic objects in the real-world space. For example, "the GUI and how it was hard to place objects;" "needs better controls "; "the vertical field of view was so small that many apps didn't fit/were unusable without continuous adjusting;" and "if my hand was too close to my face, the app couldn't function."

Among the survey participants, lack of flexibility was experienced most by high school students, followed by graduate and undergraduate students. Among these participants, a high school student suggested that "you can't move another window at the same time," which reflects the lack of flexibility in navigation and control. Undergraduate and postgraduate students highlighted the difficulty in choosing options in a mixed reality environment. Findings related to lack of flexibility corresponds with the system quality characteristics (Al-Busaidi, 2012) while learning in a mixed reality environment. From the perspective of learners, flexibility is one of the significant factors in the success of a learning environment. Hence, developers of mixed reality need to focus on the flexibility of the mixed reality devices to meet the diverse learning needs.

4.2.3 Accessibility

Accessibility is defined as the extent to which a system is available for users with diverse needs to access content (Al-Busaidi, 2012; Bradbard & Peters, 2008). The lack of accessibility in the mixed reality environment is demonstrated as a barrier. The students experienced some difficulties during their interaction with HoloLens in a mixed reality environment. Limited screen size, volume, headache, unresponsiveness, eye strain, and discomfort wearing the headset were some of the difficulties faced by the students. Some examples are as follows: "found it hard to use as I was wearing glasses and it did not fit, making my head/eyes uncomfortable;" "headset very heavy and distracting;" "it was heavy, and it hurt my neck;" "not one of the usable equipment for people who have bad eyesight;" "device-specific problems: weight, small view finder, speakers difficult to hear;" and "not one of the usable equipment for people who have bad eyesight." Accessibility issues can also be classified as ergonomic issues. One student quoted "poor ergonomics." Field of view and related ergonomics also came up as barriers. For example, "the field of the view could have been improved by being made horizontally larger;" "if you stood too close to a wall it was hard to see everything;" "field of view too small;" "screen was too small;" and "the screen was limited to a small size." Resolution of the holograms also appeared in their feedback: "resolution could be better" and "Can't see much as low-quality digits." The mixed reality environment can be more interactive with the voice application, and HoloLens is controlled using Cortana. However, the efficiency of Cortana in recognizing different accents of diverse users is also important. A few students had issues using voice commands. For example, "being able to talk to Cortana" and "understand I couldn't use Cortana." Students with visual or hearing impairments need to be considered. Accessibility for students who experience migraines or other health issues who wear glasses, or who have movement impairments needs to be considered. As illustrated in Figure 4, undergraduates had the most concern regarding accessibility issues, followed by graduate and high school students. Previous studies have already highlighted the accessibility issues of the head-mounted devices, as this affects the level of user immersion (Martin et al., 2020). The designers of mixed reality devices can address these issues to optimize the wellbeing of users and accessibility of mixed reality devices. Further, technological development will enable a more integrated mixed reality embodied learning environment. Learning designers will need to make sure that they design the best options to facilitate better accessibility to enrich the learning experience.

Reliability and response time were not identified as barriers for the graduate students, while few issues were evident for the undergraduate and high school students. The main lack of reliability and large response time issues highlighted by the students were "control failure" and "glitches." A comparison of the percentage of barriers identified for the three different cases is given in Figure 4. A small percentage of students explicitly mentioned that they did not experience any barriers: for example, "its all pretty cool" or "no bad feedback." Although it is a small ratio, it is important to note that students do fully accept learning in mixed reality environments as they explicitly specified that they do not find any barrier. Unclassified cases are those where the text is not related to barriers such as "N.A." or left blank.

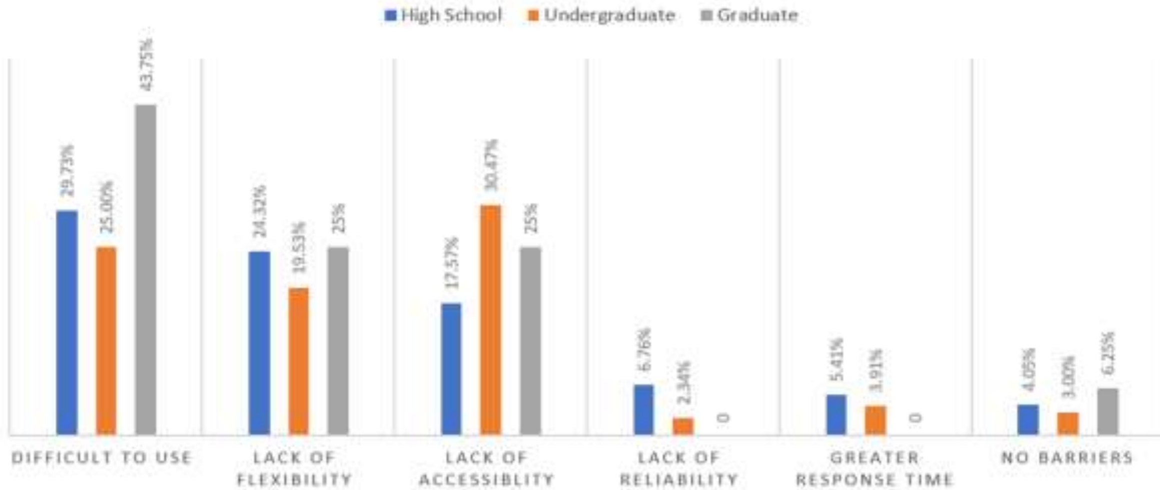

Figure 4 Barriers of Students Learning in a Mixed Reality Environment

To gain insight regarding the barriers that students would like to overcome, the answers to the question: "What would you like to see changed or added to this application?" were analyzed. The answers were a follow up on the barriers identified. Some students left their answers blank (29%). A few students (6%) also specifically answered that no improvements were required. The second highest response was that they would like to have more applications, such as tours of places, games, and educational materials, in the mixed reality environment (14%). This is also a positive reflection from students. Easier controls of the mixed reality interface, increased field of view, easier to wear, more lightweight, and improved design of the device were the technical recommendations. Easy control of holograms and easy navigation were the suggested improvements from students. Students also wanted to have more collaboration and group work and visibility of others work to have an engaging work atmosphere. Accessibility issues also need to be addressed, as highlighted by students wearing glasses. An important recommendation is the need for more training and tutorials to make the students more familiar with the mixed reality learning environment. Familiarity with the device will help them dedicate their time to the learning content rather than the interaction and use of the device. Table 6 provides a summary of the areas that were identified by students that need improvement.

Table 6. Barriers and Improvements Suggested by students

Barriers Identified	Improvements Suggested by Students
Lack of flexibility	• Facilitate more collaboration and group work
	• Multi-tasking and multiple application
Difficult to use	• Easy to wear and lightweight
	• Quality of graphics
	• Increased field of view
	• Hand gestures and voice commands
Lack of accessibility	• Easy to wear for those with glasses
	• Responsive controls
	• Training

To conclude, based on the findings, it is evident that the mixed reality device and the interactive and immersive holograms influenced the students to have a positive learning experience. The sense of presence and the control of holograms with hand, voice, and body movements increased the amount of flow experienced by the learner. Hence, the design of an immersive learning experience, well-calibrated content with a balance of skills and challenge, and an inclusive learning environment enhance the flow of learning.

5 Discussion

This study presents a multi-site case study by evaluating feedback from 223 students on their learning experiences after using Microsoft HoloLens—a mixed reality device—in their classroom. Affordances and fatigue are major themes identified, and they include a set of constructs that act as drivers of and barriers to the flow of students’ learning experience. These two themes are explained below.

1. **Affordances:** Mixed reality affordance is achieved through interactivity, immersion, presence, and innovativeness. Interactivity is experienced by students in the form of designing and controlling objects which will lead to a new way of learning. Interactivity leads to embodied affordances of the mixed reality environment and will improve the quality of content and enhance students’ learning experience (Johnson-Glenberg, 2018). Immersion is experienced through engagement, fun, and visualization, which will help to recollect learning content easily. Embodied affordances of gesture and manipulation in a mixed reality environment will improve motor planning and mental stimulation and lead to an immersive learning experience. Presence is characterized by the ability to adapt to a new environment without any restrictions. The sense of presence is an important measure with respect to mixed reality environments and will correlate with higher affordances of embodied learning. Innovativeness is characterized by the curiosity to experiment with new ways of learning and the learning environment.
2. **Fatigue:** Mixed reality fatigue is due to difficulty to use, lack of flexibility, and accessibility. Difficulty to use is mainly attributed to haptic and learnability issues faced by learners while they interact with the mixed reality environment. Haptic issues include non-response to hand gestures, while learnability issues include the difficulties experienced by the first-time users of a mixed reality device (Johnson-Glenberg, 2018). Measures to increase learnability and improve ergonomics will help reduce the barriers related to mixed reality fatigue. Lack of flexibility reflects the difficulties experienced by students in selecting menu choices on the interface of a mixed reality application and maintaining the spatial orientation of objects created in the mixed reality environment. The lack of accessibility reflects ergonomic issues, along with the specific physical properties of a mixed reality device. From the perspective of learners, flexibility and accessibility are important factors that contribute to the success of any learning environment. Hence, there is a need to avoid fatigue by improving the learnability, flexibility, and accessibility of the mixed reality environment to improve the learning experience.

The design principles derived from the findings of this study will contribute toward designing the use of mixed reality to effectively build new embodied learning environments.

DP1: Principle of Embodied Pedagogy

The principle of embodied pedagogy focuses on the design of the flow of learning, learning task, assessment, and learning outcome. This can be accomplished by scaffolding learning activities, embedding the learning task with interactive and immersive activities, and linking the tasks with their assessment and learning outcomes. A balance between the skills required and challenges faced while completing the activities will increase the autotelic learning experience of users in a mixed reality environment.

DP2: Principle of Learner Accessibility

The principle of learner accessibility focuses on the design features to enhance the user experience. This can be accomplished by providing orientation to the mixed reality environment and making sure the user goes through a learnability phase. Detailed briefing of the activity in preparation is required to focus on the efficiency of the learning outcomes. Alternative tasks and flexibility in choosing and adapting to the mixed reality learning environment are important to improve the learning experience of the learner.

DP3: Principle of Technology Affordances

The principle of technology affordances is in facilitating a successful learning environment. The sense of control, presence, gesture, and manipulation improve learnability and retention in a mixed reality environment. The affordances with respect to ergonomics and extensive use and the avoidance of the barriers to mitigate fatigue are important for experiencing an effective mixed reality learning environment.

A limitation of this study is that the long-term learning effects were not examined. This study used an authentic learning experience in the classroom with different age groups to evaluate users’ learning experiences. Directions for future research are as follows. First, there is a need to formulate specific design experiments based on the factors that enhance interactivity and immersion using embodied learning. Second, there is a need to explore the effects across various groups by including control groups to evaluate real-time cognitive learning experiences. Third, a continuous learning experience in a mixed reality environment will enhance the usability of the device and help to evaluate the effectiveness of learning outcomes. Hence, developing a series of assessment tasks will also help measure both learning and retention. Fourth, a quantitative analysis of the influence of factors such as skills, control, interactivity, immersion, presence, and enjoyment on improved learning experience will help us understand the significant factors that improve the flow of learning. Finally, mixed reality technology is expanding toward creating digital twins in virtual environments and embedding embodied devices in our lives. The field of view in HoloLens 2 has improved, from 35 to 52 degrees. HoloLens 2 enables eye tracking and hand tracking as opposed to the limited gesture tracking in the first version of HoloLens (Microsoft, 2021). The eye-tracking data collected will help provide a new level of understanding within the holographic learning experience (Lu, Perdomo, Jiang, & Zheng, 2020). Designing new learning environments that embed full-body interactive tasks to achieve learning outcomes is the next challenge (Pappas & Giannakos, 2021). Thus, future research will need to bring together experimental psychologists, educational designers, and technologists to work towards an integration of behavioral and DSR. There is a need to effectively build new embodied mixed reality learning environments. The design principles proposed in this study will aid educators and implementors to enhance the learning experience.

6 Conclusion

In this study, we applied flow theory with the DSR framework to identify the drivers and barriers of students' learning in a mixed reality environment. In addition, we presented three different cases in three different age groups to understand the various factors that influence students' adoption of a mixed reality environment for learning. Overall, we conclude that the pedagogical design, technical support, and coordination play important roles in ensuring that students experience the flow of learning embodied in the mixed reality environment.

The theoretical implications are as follows. First, it is important to identify and differentiate the person experiencing the flow, the tasks, and the type of artifact. In this study, the artifact is the mixed reality learning environment that assists students in improving their learning experience. Understanding knowledge embodied by measuring the constructs of flow theory helped to realize the embodied learning experience, as presented in Table 5. Second, the user experience and perception of the adoption of a new technology and the knowledge embodied in the flow antecedents, flow experience, and flow consequences are highlighted as drivers of using a mixed reality environment for learning. The drivers related to user experience were found to be interactivity, immersion, presence, and innovativeness. These constructs were proposed by Walsh and Pawlowski (2002) with respect to a VR environment, and this study reconfirms the drivers of learning in a mixed reality environment, as presented in Figure 3. The findings reveal how students interact with respect to the technology to accomplish their learning objectives and enhance their learning experiences. Third, the three case studies clearly provide a relative comparison of the factors that influence students' learning experience in the mixed reality environment among different age groups and knowledge levels. Fourth, Table 6 presents recommendations to overcome barriers faced by students. Finally, the two themes that evolved with respect to affordances and fatigue of the mixed reality learning environment and the three design principles derived from the findings of this study will contribute toward designing mixed reality learning environments in the future.

Practically, conceptualizing and establishing sustainable innovation in pedagogical practices rely on equity of access to both the innovations and the technologies. HoloLens in the classroom supported digital inclusion and provided students with a mixed reality experience. A well-designed and optimal pedagogy for the new mixed reality environment plays a significant role in enhancing the learning experience. As discussed by Johnson-Glenberg and Megowan-Romanowicz (2017), the amount of sensorimotor engagement, gestures compatible with the content, and the amount of immersion experienced by the user are the degrees of embodiment by the user. The drivers identified in this study align with the degrees of embodiment experienced by the students in a mixed reality learning environment. Thus, there is an immense value for educators and designers to cater toward embodied learning by finding ways to embed interactive physical activity in the learning tasks by using a mixed reality learning environment. This will facilitate immersive learning and effective engagement. Large-scale integration of mixed reality learning environments will require support with respect to budget and governance to successfully implement and test the learning environment. The technical limitations and users' proficiency were determined to be barriers that cause fatigue (Gasques et al., 2021). These limitations can be addressed using a revised learning design that improves the affordances of the learning environment and diminishes the fatigue experienced by learners. This study lays a foundation of design principles for educators and designers to enhance students' learning experiences in mixed reality learning environments.

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