Fighting Fires with Mixed Reality: The Future of Fire Safety Training and Education

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Abstract

Extended reality technologies have made a significant impact in various educational domains, including medical sciences, built environment, and the humanities. Fire-extinguisher training (FET) for non-professional firefighters can expose trainees to dangerous situations, including high temperatures, fire, and smoke. In this paper, we explore the use of mixed-reality (MR) technology for FET. We incorporate sensor-based environmental information to provide a safe, immersive, firefighting scenario that simulates realistic conditions.

We report on the development of a Hololens-based FET application using the Unity3D engine and MR toolkit (MRTK) plugin. The FET has two modes: training and application. During the training mode, trainees learn how to use different fire extinguishers through an interactive holographic experience. In the application mode, they use the holographic fire extinguisher to extinguish virtual fires in the real environment. Fifty participants took part in the study. Each participant engaged with two training modalities: traditional (video-based) learning and MR-based FET (MR-FET). Participants were surveyed about different elements of their MR-FET learning experience, including their level of motivation, engagement, interest, comfort, and overall experience.

The survey results reflect a positive experience with the MR-FET, as evidenced by a mean rating of 4.32 out of 5.0. The participants rated their motivation, engagement, and attraction with the training experience at 4.59, 4.39, and 4.49, respectively. These findings suggest that the participants were highly motivated to use MR-FET, had a strong engagement with the presented material, and were significantly interested in the overall learning experience. Nevertheless, concerns were raised regarding the Hololens not being particularly comfortable (mean rating of 3.69 for comfort). Conversely, only a very low proportion of participants reported experiencing symptoms of cybersickness (6.8%), indicating that MR could be a feasible replacement for virtual reality (VR)-based FET.

This study proposes an MR-based firefighting training tool that could reduce the motion-sickness issues common to VR-based training. Furthermore, the simulated fires can be integrated with objects in real-world environments, enhancing the immersive experience, and minimizing the physical risks.

Keywords: education; firefighting safety training, human-computer interaction, mixed reality

1 Introduction

In the post COVID-19 pandemic era, the education sector transitioned from traditional classroom-based teaching towards online learning. However, based on a survey by Serhan (2020), students are generally unhappy with using an online-based conferencing platform, citing the lack of engagement, low quality sessions, and large number of distractions as some of the reasons (Serhan, 2020). Thus, immersive technologies in education could prove to be indispensable in promoting engagement in learning (Willcott, 2021).

1.1 Background

The applications of immersive technologies, i.e., virtual reality (VR), augmented reality (AR), and mixed reality (MR), have taken place in many educational fields, including medical sciences (Gerup et al., 2020), architecture (Yilei, 2020), and the humanities (Hou, 2019), amongst many others. VR and AR have started to become commonplace in the field of education since they offer a digital reality that blends our reality and virtuality through digital simulations (Gurevych et al., 2021; Hamilton et al., 2020; Quintero et al., 2019; Steinicke & Wolf, 2020). VR and AR still have their challenges, such as motion sickness, lack of real-world spatial relation in VR, and the separation of the real and augmented world in AR (Bricken, 1991; Mandal, 2013; Rokhsaritalemi et al., 2020). MR tries to address these issues by providing a mixture of the best from each of the digital realities.

MR through Microsoft Hololens, in particular, has seen its uses in the STEM (science, technology, engineering, and mathematics) field, especially in regard to practical sessions like training and labs (Elsom, 2017; MacKay & West, 2020). The use of holograms to replace real equipment minimizes safety risks, such as when using heavy machinery where injuries could happen, or fire-safety training with the risk of getting burns. Using Hololens enables simulating a scenario, such as a fire, and applying that scenario virtually, but directly, on the real-world using holograms.

This study aims to investigate the application of MR using the Hololens headset for FET simulation in the university environment. Since MR is best used to simulate practical tasks, the fire-extinguisher training (FET) has been chosen as the scenario for this study. This decision was based on several reasons, including: (1) real fire extinguishers do not include the real experience in real fire, because it is dangerous and impractical; and (2) fire extinguishers are limited in number and in some cases quite costly. This study addresses the strength and effectiveness of using MR in FET compared to traditional paper-based delivery methods.

By using MR to address this, the challenges are virtually mitigated using 3D models and simulations, and no additional cost of procuring fire-extinguisher is incurred. Fire simulation is also entirely virtual and thus, the danger aspect of fire is also nullified. Lastly, using MR would allow anyone with access to the device to experience first-hand, real-time FET.

1.2 Related Work

MR has been used in the field of education and training, with some claims that it improves learning outcomes and is transforming how learning is done. Although MR could be deemed still an emerging immersive technology, there have been instances where it has been used in the education industry. According to Microsoft, there is a 22% improvement in test scores, and a 35% increase in engagement and retention, when using the MR technology (Microsoft, 2021).

A study done by Hughes et al. (2005) indicated that using MR technology in a sea-creatures experience (viewing and learning about various marine life) in the Orlando Science Center's DinoDigs exhibition hall encouraged longer and more repeated visits to the exhibit. Furthermore, 88% of the respondents of the study reported that using MR increased the entertainment value and allowed them to learn in an entertaining way. A more recent finding by Leonard and Fitzgerald (2018) showed that students in a secondary school setting feel that using HoloLens in education increases the content engagement and overall could have a positive impact on learning. They also found that teachers in the same setting were increasingly able to identify ways to redesign the learning environments, and to try to connect their students with the new technology. Bacca et al. (2014) and Radu (2014) both further validates the study by finding that AR and MR technologies were both found to be positively impacting learning and motivation, amongst other benefits.

According to a review by Hamilton et al. (2020), the use of immersive technologies is mostly concentrated in the field of science (45%), while its use in safety education is the lowest (3%). Furthermore, the study cited that the ability to repeatedly practice a procedure in a safe environment whilst expending few resources may be one of the best benefits of using immersive education. The United States CDC (Centers for Disease Control and Prevention) has reported that, between 2001 and 2014, approximately 11% of fire fighter fatalities were related to training and drills (CDC, 2016). Equipment drills was reported to be one of the three leading types of activity associated with the fatalities (USFA, 2015). Thus, it is important to find a safer method for training firefighters, for which MR might be the answer.

There are several existing MR applications in education. Lifeliqe (2021) is a HoloLens-based education platform that provides classroom MR solutions, including interactive 3D models and lesson plans available directly on the Hololens device. Lumilo (Holstein et al., 2019) is a pair of glasses based on the Hololens that allows teachers to see real-time analytics about the class being taught by combining MR and AI technologies (Cebzanov, 2020).

2 Methods

This study aims to provide a preliminary understanding of how MR-based learning is being received by the participants compared to traditional learning methods. It also aims to obtain feedback about the MR-based FET (MR-FET) and user experiences (UX). The study has been reviewed and approved by the university's research ethics committee, following the process for ethical review governed by the university's code of research conduct and research ethics (UNNC, 2021). The process for the formal study session is shown in Fig. 1.

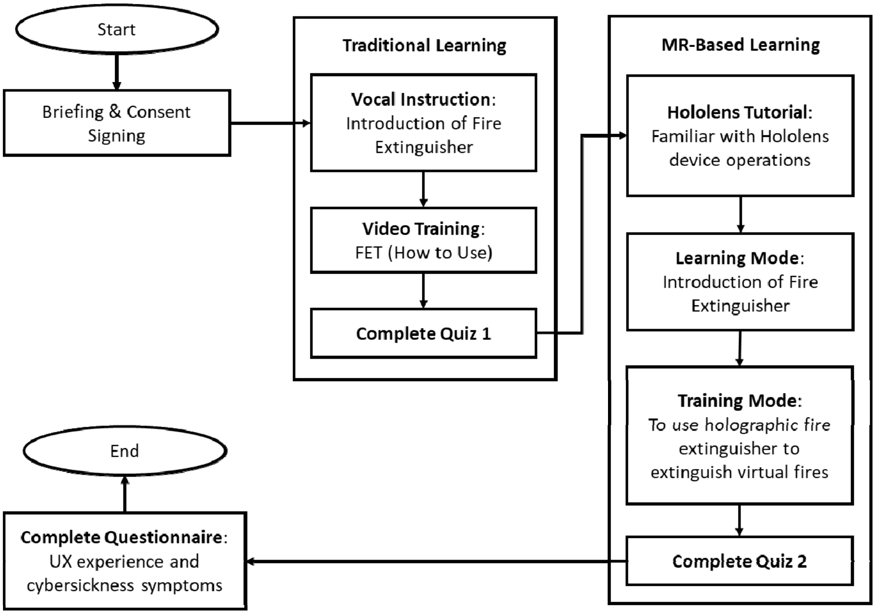


Fig. 1. Flowchart of the study.

2.1 Participants

The volunteer-sampling method, which could be considered a subset of the convenience sampling method, was used to recruit participants to join the study (Taherdoost, 2016). This sampling method was chosen due to it being the least time-consuming and least expensive compared to other methods, such as simple random sampling or structured sampling. This, however, may increase the bias in the participants, since depending on how the recruitment was conducted, certain types of individuals may be favored more than others, resulting in a skewed sample pool. To address the possible bias, the volunteer-sampling method used in this study was tweaked from the convenience sampling to include a larger proportion of strangers, instead of acquaintances (friends, colleagues, and family). This was done through sending a recruitment email to the entire student population in the university, which was hoped to increase the randomness, and give an equal probability for everyone to be selected in the sample.

A total of 59 participants were recruited from various study background in the university using the volunteer-sampling method. The participant gender distribution was roughly equal between male (n = 28) and female (n = 31), with no participant identifying as non-binary. Amongst these participants, 15 came from the Centre for English Language Education (CELE); 26 from the Faculty of Science and Engineering (FoSE); six from the Faculty of Humanities and Social Science (FHSS); and 12 from the Nottingham University Business School China (NUBS). These included: 15 students from Preliminary Year (Year 1), 17 from Qualifying Year (Year 2), nine from Part 1 (Year 3); 15 from Part 2 (Year 4); and 3 from postgraduate level (Ph.D. students). Table 1 summarizes the demographics of the participants.

Table 1. Summary of participants recruited for the study.

Faculty	Year 1	Year 2	Year 3	Year 4	PhD	Total
CELE		-	-	-	-	15
FoSE	-	7	6	10	3	26
FHSS	-	2	1	3	-	6
NUBS	-	8	2	2	-	12
Total	15	17	9	15	3	59

It is worth noting that, amongst the participants pool, about 78% (46 out of 59) had had previous experience of using at least one of the three immersive technology platforms (VR, AR, and/or MR). Each participant was informed that their participation in the study was entirely voluntary, and that they could withdraw at any time. This information was repeated to the participants on multiple occasions, including in the recruitment email, and verbally during the formal study session. All information collected has been kept strictly confidential, following the requirements for ethical data storage.

2.2 Design of Learning Methods

The FET was divided into traditional learning and MR-based learning methods. Both methods had similar session lengths, with the MR-based learning session taking about five minutes longer to allow time for participants to adapt to the Hololens hand-gesture operations.

2.2.1 Traditional Learning

The traditional learning session was designed to mimic a short lecture-style FET briefing. This session included verbal instructions, a set of presentation slides, and a brief video demonstrating how to use a fire extinguisher. There were also several other elements found in a traditional learning setting. The short presentation introduced participants to different classes of fire and various types of fire extinguishers, including the suitability of different fire extinguishers for various types of fire.

2.2.2 MR-Based Learning

The MR-based learning presented similar content to the traditional learning session, with immersive elements being incorporated through MR. These elements included animations of the 3D models and FET simulation, in which participants could attempt to use the virtual equipment to extinguish virtual fires.

2.2 Design of Pilot Study

Each session was arranged in groups of five participants, with each participant taking approximately 45 minutes. At the start of each session, all participants were briefed on the project information, and asked to give their consent. The voluntary nature of the project was also reiterated. Had any participant chose to withdraw at this point, they would have been asked to leave the venue, and all related data and information would have been deleted. Participant information collection was done to collect the basic demographic information, such as gender, age, and study background.

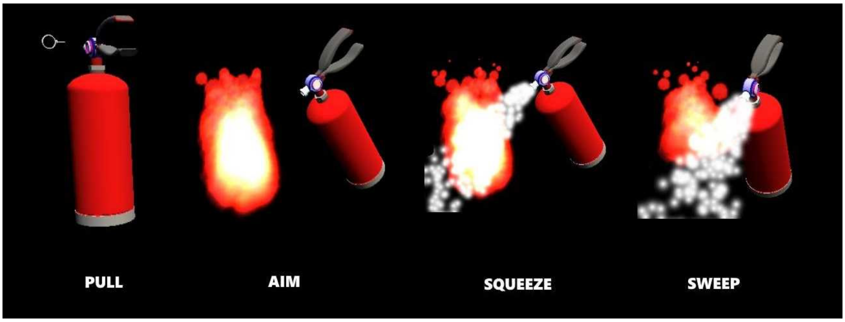
After the briefing and consent section were completed, participants were then invited to join the traditional learning session, after which they were asked to complete the first quiz. Participants then continued to the MR-based learning session, where they were first taught about the hand gesture operations of the Hololens device, before starting the FET. The MR experience is depicted in Fig. 2, where participants are using the Hololens and interacting with the virtual contents. After they completed the MR-FET session, they were asked to complete a UX questionnaire and take a second quiz. A researcher was present for all the sessions, to assist the participants.

Fig. 2. Interaction of participants with Microsoft Hololens device.

The MR-FET app was designed with both a learning and a training mode. The learning mode presents the user with holographic fire extinguishers, which they would be able to view and learn specifics about. The holographic equipment would be shown in a “showcase”-like fashion, where they can be rotated and switched into an exploded view to show how the equipment looks like when disassembled. The training mode allows users to use holographic fire extinguishers to extinguish virtual fires. The interaction with the holographic fire extinguisher was designed to simulate the real-life counterpart but adjusted for using the hand gestures as interaction method. The virtual fires were designed to have distinct health properties, i.e., different fire sources and types took different amounts of extinguishing agent and different amount of time to extinguish. The main purpose was to simulate how real fires behave, since not every fire would take the exact same resources to extinguish.

Fig. 3 shows screenshots of the MR-FET app learning mode, developed using Unity modeling tool. The study used Mixed Reality Toolkit (MRTK) to deploy the Unity app into the Hololens headset. This toolkit allows various built-in MR features, such as solver functions to track head or hand movements, to be implemented quickly and easily. Fig. 4 shows screenshots of the deployment of the app in the Hololens headset.

(a)



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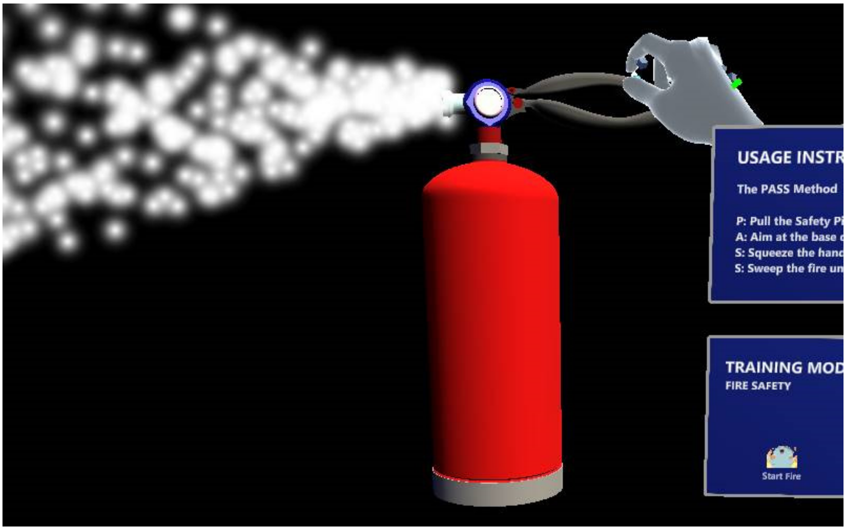
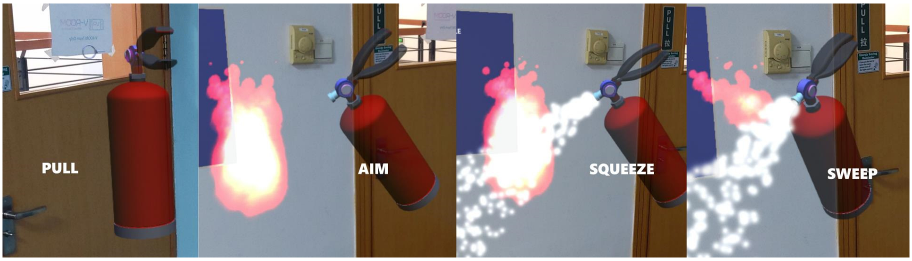


(c)

Fig. 3. Screenshots of developed fire-extinguisher using Unity which include (a) fire related knowledge learning, (b) used of fire-extinguisher, and (c) practice of interaction with virtual fire-extinguisher.

(a)



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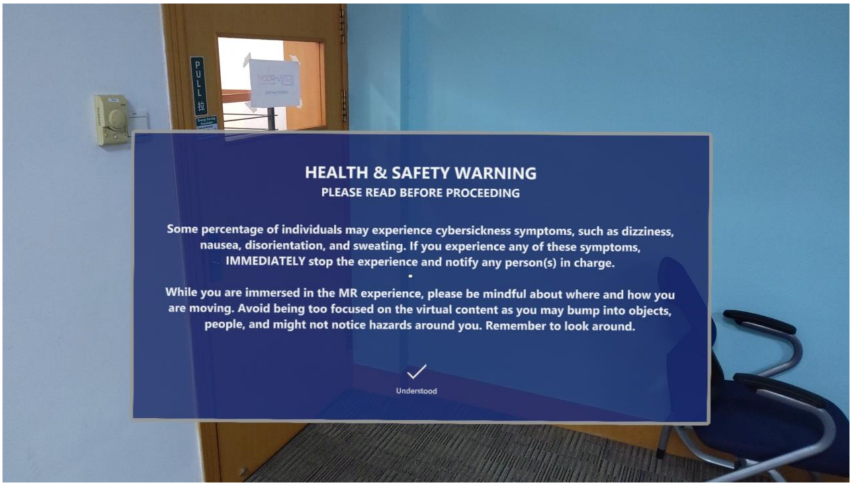

(c)

Fig. 4. Screenshots of the deployment of app in Hololens headset.

2.3 Quiz and Questionnaire

Two quizzes, each comprising five multiple choice questions, were created to investigate the knowledge retained after each learning session. The difficulty of these questions was set to be roughly the same, since both the traditional and MR-based learning sessions present very similar learning content.

Meanwhile, a modular extension of the user experience questionnaire (UEQ), known as UEQ+ (Schrepp et al., 2021), a standardized framework to measure the UX. This framework was chosen because of the completeness of the resources provided, as well as that the framework is supported by relevant studies (Laugwitz et al., 2008; Schrepp et al., 2014). The basic UEQ measures six UX: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. However, for the purpose of gaining more meaningful and insightful data, the UEQ+ modular extension was used instead, adding four more scales (acoustics, usefulness, quality of content, and clarity). These scale measures are described in Table 2.

Table 2. Description of UEQ+.

Scale	Description
Attractiveness	Overall impression of the MR-FET app.
Perspicuity	How easy to learn or get familiar with is the app?
Efficiency	How much effort does user need to achieve the task?
Dependability	How much control does user feel while interacting with the app and does the interactions provide a robust and predictable experience?
Stimulation	How exciting and motivating is the MR-FET app for users?
Novelty	Is the MR-FET app interesting and creatively designed?
Acoustics	Impact of the sound effects used in the app towards user experience.
Usefulness	Do users find advantages in using the MR-FET app?
Quality of Content	How good and updated is the information provided in the MR-FET app?
Clarity	User impression on the user interface order, structure, and visual complexity.

3 Results and Discussion

The obtained data were initially pre-processed to compile the scores of quizzes and questionnaires. Firstly, the rating of the questionnaire was scaled from 1 to 5, where 1 indicated the lowest (i.e., no motivation), and 5 the highest (i.e., high motivation). The statistical results of the rating (including the values of mean, mode, median, minimum, and maximum) are presented in Table 3.

Table 3. Statistical analysis of questionnaire ratings.

Aspect	Mean	Mode	Median	Min	Max	Male	Female
Motivation	4.59	5	5	3	5	4.61	4.58
Engagement	4.39	5	5	3	5	4.39	4.39
Attraction	4.49	5	5	2	5	4.54	4.45
Comfort	3.69	4	5	2	5	3.71	3.68
Overall	4.32	5	4	3	5	4.29	4.35

The participants noted that the MR-FET app was valuable for their learning, particularly in the context of FET (mean overall rating of 4.32/5.0). This was further reinforced by the mean ratings for motivation (4.59), engagement (4.39), and attraction (4.49) which indicated that participants had higher motivation to learn, high engagement with the contents delivered, and had good learning experiences. These findings are consistent with an earlier study published by Hughes et al. (2005), which used MR technologies in a sea-creatures experience (knowledge learning about marine life). According to that study, 88% of those surveyed believed that MR added an entertainment factor to the learning process, and 83% agreed or strongly agreed that they learned more about the subject when compared to when they did not use MR.

Despite the high overall rating, several participants found that using the Hololens was not particularly comfortable, as indicated by the comfort rating of 3.69 out of 5. A participant noted that the headset was slightly uncomfortable, and a verbal follow-up attributed the discomfort to the weight and the heat generated after a certain duration. Another participant commented that the device kept falling, which might be due to the straps being too loose. The responses were also analyzed based on the genders, with both giving almost identical overall ratings, indicating that gender did not have a significant impact on the UX with MR-FET. Amongst the four faculties, participants from NUBS rated the overall experience with the highest rating (4.67), followed by CELE (4.40), FoSE (4.23), and lastly FHSS (3.83), as summarized in Table 4.

Table 4. Statistical analysis of questionnaire mean ratings based on faculty.

Aspect	CELE	FoSE	FHSS	NUBS
Motivation	4.60	4.54	4.67	4.67
Engagement	4.27	4.35	4.50	4.58
Attraction	4.67	4.31	4.50	4.67
Comfort	3.93	3.50	3.17	4.08
Overall	4.40	4.23	3.83	4.67

3.1 Traditional vs MR-Based Learning Results

Table 5 presents the results of the first quiz (traditional learning method) and second quiz (MR-based learning method) for participants. The participants scored better in the first quiz. Table 6 shows the changes of score between the quizzes. A value of -1, for example, indicates that a participant got one less question correct in the second quiz compared to the first quiz.

The mean performance of changes was -0.102, showing a general worsening of their quiz results, which may be attributed to a range of factors including, but not limited to: information retention; attention span; and a possible increase in distracting components in the MR app setting. The value of -0.102 corresponds to a 2% drop in the mean marks. A t-test was utilized to verify the statistical significance between the quiz results, as depicted in Table 7.

Table 5. Performance of the quizzes for based on the number of participants that answered the quizzes correctly.

Question	Quiz 1		Quiz 2	
	Total	%	Total	%
A	54	91.5%	48	81.4%
B	44	74.6%	52	88.1%
C	56	94.9%	52	88.1%
D	51	86.4%	57	96.6%
E	57	96.6%	44	74.6%

Table 6. Comparison of score changes between two quizzes.

Number of Changes	Total
-5	0
-4	0
-3	0
-2	5
-1	16
0	23
+1	12
+2	1
+3	2
+4	0
+5	0

Table 7. Participant t-test results.

Metric	Value
Mean	-0.102
Std. Dev.	1.094
t	0.714
df	58
Sig. (2-Tailed)	0.478

Taking $\alpha = 0.05$ and the hypothesis that:

$$H_0\text{: } \mu_d = 0$$

This study concludes that, since the $p = 0.478 > \alpha$, there is insufficient evidence to support the rejection of the null hypothesis (H_0) which indicated that the significance of the statistical analysis results did not strongly support the differences of quiz results due to MR but may have occurred purely by chance due to the difficulty of the quiz questions.

3.2 UX Results

The UX results from the UEQ+ questionnaire is presented in Table 8 and Fig. 5, with the rating scale range of -3 to +3. A mean value of less than 0 indicates that participants had a negative attitude to the MR-FET app; greater than 0 indicated a positive attitude; and a value of 0 indicated neutrality regarding the MR-FET app. For instance, a mean value of -3 on the attractiveness scale indicated that the participants did not find the app attractive, and a mean value of 3.00 on the usefulness scale indicated that participants found the app to be very useful in the FET learning context. In general, the results indicated that participants had a positive to the proposed MR-FET work, with all mean values being above 0.

The top three aspects were stimulation (2.16), clarity (2.15) and quality of content (2.08). Specifically, the participants rated that the MR-FET app could increase the motivation and excitement of learning and noted that the app sometimes had a better way of displaying content. Furthermore, the usefulness scale mean score was 2.04, indicating that the app was rated to be beneficial and useful for assisting in learning.

Table 8. Statistical analysis of UX for MR-FET app.

Scale	Mean	Variance	Std. Dev.	Conf.	Conf. Interval	
Attractiveness	1.81	1.50	1.22	0.31	1.50	2.12
Efficiency	1.61	1.92	1.38	0.35	1.26	1.96
Perspicuity	1.94	1.36	1.16	0.30	1.65	2.24
Dependability	1.80	1.76	1.32	0.34	1.46	2.14
Stimulation	2.16	1.27	1.13	0.29	1.87	2.44
Novelty	1.99	1.36	1.16	0.30	1.69	2.29
Acoustics	1.58	1.88	1.37	0.35	1.23	1.93
Usefulness	2.04	1.40	1.18	0.30	1.74	2.34
Quality of Content	2.08	1.16	1.07	0.27	1.81	2.35
Clarity	2.15	1.05	1.02	0.26	1.89	2.41

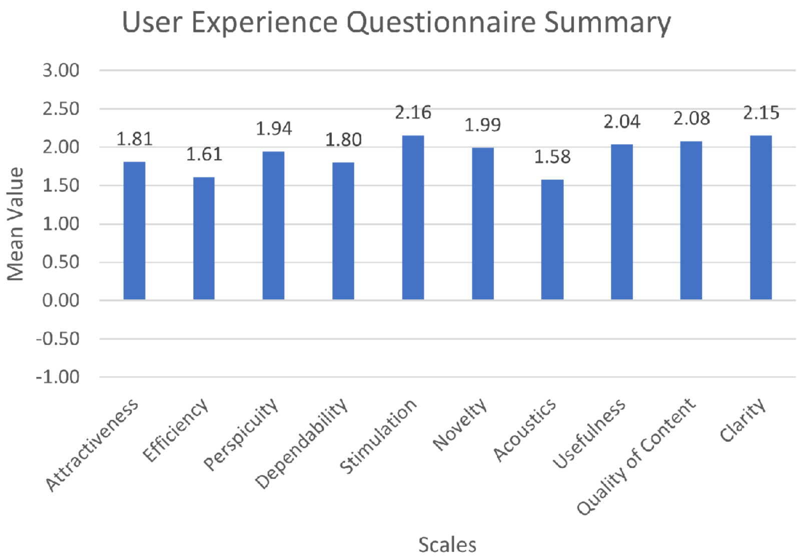

Fig. 5. Plot of UX analysis for MR-FET app

In addition, correlation and Cronbach alpha (formerly known as alpha-coefficient) analyses were performed to validate the consistency of the UEQ+ scales, as shown in Table 9. The results show that the mean Cronbach alpha values are higher than 0.7, which justified that the scales are being sufficiently consistent as suggested by (Adadan & Savasci, 2012; Griethuijsen et al., 2015; Taber, 2018).

Table 9. Consistency analysis of UEQ+ scales.

Scale	Mean Correlation	Cronbach Alpha
Attractiveness	0.54	0.82
Efficiency	0.51	0.81
Perspicuity	0.49	0.80
Dependability	0.44	0.76
Stimulation	0.69	0.90
Novelty	0.69	0.90
Acoustics	0.62	0.87
Usefulness	0.69	0.90
Quality of Content	0.52	0.81
Clarity	0.71	0.91

3.3 Cybersickness Analysis

Cybersickness is a subset of motion sickness that occurs when a participant starts exhibiting motion sickness symptoms in an immersive virtual environment (Chang et al., 2020; Takov & Tadi, 2021; Yildirim, 2019). In this study, four out of 59 participants reported experiencing cybersickness symptoms during the MR-FET session. Three participants started exhibiting symptoms roughly between 10 to 15 minutes into the session, and only one started experiencing cybersickness 15 minutes after the MR-FET session started.

Table 10. Statistical analysis of reported cybersickness symptoms.

Symptoms	Mean	Min	Max
Headache	1.50	1.00	2.00
Fatigue	1.00	1.00	1.00
Eye Strain	2.25	1.00	4.00
Loss of Balance	2.00	1.00	3.00
Nausea	2.25	1.00	4.00
Dizziness	2.50	1.00	4.00
Sweating	1.50	1.00	3.00
Disorientation	2.00	1.00	4.00
General Discomfort	2.00	1.00	4.00
Stomach-ache Awareness	1.00	1.00	1.00
Vomiting	1.50	1.00	3.00

Participants were also asked to rate the severity of their symptoms and the results are summarized in Table 10. The ratings indicated that the symptoms of dizziness, nausea, eye strain, loss of balance, disorientation, and general discomfort were amongst the most severe, receiving the maximum rating of 4 by most participants. The four participants who experienced the cybersickness symptoms provided different reasonings. One of them attributed their symptoms to the visual or graphics quality, based on their comment that the images blurry. The second participant mentioned that the virtual scene was not very clear and was somehow moving from time to time. This situation suggests the possibility of software bugs in the MR-FET app that may cause result in those scenes not being anchored properly in virtual space. One participant indicated that he/she felt sick because the virtual object (fire-extinguisher) did not move properly on the first click, suggesting that the participant may not have had sufficient time to become familiar with the hand gesture interaction features of the headset. The last participant was not able to identify any specific potential cause of his/her cybersickness symptoms. Although the number of participants experiencing cybersickness was low (6.8%), it is still important to address the issue and possibly minimize and mitigate the occurrence of cybersickness in future MR-based app development.

4 Conclusion

This study has examined the impact of FET using MR, compared with traditional methods (PPTs and video), to increase the motivation and engagement of users in a training program. We conclude that the MR-FET app was popular with participants. In the comparison of the two different learning modes, the results were inconclusive, due to the lack of supporting evidence to justify the training performance based on the scores of quizzes. In general, it seems that MR technology has a very broad potential to be a breakthrough solution towards improving teaching and learning model by introducing an immersive setting where learners can interact, and experience first-hand supported by holographic elements in the real world. Since this project has explored the topic more through a computer science-oriented perspective, an interdisciplinary investigation may result in even more comprehensive and impactful insights being discovered.

The findings suggest that it may still be premature to implement MR technology in a classroom setting. This could be attributed to the problems highlighted in the study and how participants perceive the technology. There are still many aspects of MR app that should be explored fully for the technology to be completely relevant in education. The potential for using immersive technology in the education field is high, crediting the potential benefits that have been investigated and demonstrated through this study.

Throughout the study, various problematic aspects and areas for potential improvements have been identified, such as bugs and issues regarding holographic content interactions. Our future work will include conducting a comprehensive study to investigate the relations of quizzes and app design for the training performance assessment.

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