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ORIGINAL ARTICLE

Designing and evaluation of a mixed reality system for crime scene investigation training: a hybrid approach

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Abstract

Police investigation in real-life crime scenes is an essential aspect of forensic science education. However, the practicality of bringing young investigators to actual crime scenes is often hindered by the costs and challenges involved. In order to overcome these obstacles, new technologies such as mixed reality (MR) are being explored as potential solutions. MR technology offers an interactive and cost-effective way to simulate real-life crime scenes, providing a valuable training experience for young investigators. This paper presents a novel design of a MR system using Microsoft HoloLens 2.0, which is tailored to work in a spatial 3D scanned and reconstructed crime scene using FARO point cloud 3D scanner X130 blended with photogrammetry techniques. The system was developed through the lens of Experiential Learning Theory and designed using a participatory approach, providing a cost-effective solution to help trained Kuwaiti police officers enhance their investigative skills. In order to evaluate the system's user experience and user interaction, the Questionnaire of User Interaction Satisfaction and User Experience Questionnaire were utilised. Forty-four young police officers evaluated the system. Police students showed positive levels of satisfaction with user interaction and overall user experience with minimal negative feedback. Female students showed higher satisfaction with the overall impression compared to male students. Based on the positive feedback regarding the system expansion, the system will be taken into the commercialisation stage in the future to be provided as an essential tool for crime scene education and investigation practices.

Keywords Mixed reality · User interaction · User experience · Crime scene · Investigation training · 3D scanning · Photogrammetry

1 Introduction

The goal of crime scene investigation is to gather and preserve evidence from the scene of a crime in order to connect it to the perpetrator. Police investigators and forensic professionals use various tools and techniques to collect evidence in a safe and traceable manner (Streefkerk et al. 2013). The failure to find and preserve physical evidence can result in the loss of forensic value and the inability to identify the offender. According to a UK Home Office report, half of the cases were dropped due to a lack of supporting evidence. Thus, experts in forensic investigation are trained to use forensic tools to gather evidence from crime scenes, such as fingerprints, gunpowder, and blood droplets (Trushchenkov et al. 2021). Research has shown that tangible evidence plays a significant role in linking suspects to crime scenes,

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accounting for 77.6% of homicide cases and 90% of felony crimes (Peterson et al. 2010).

Training investigators on-site is a difficult task as crime scenes are delicate, and evidence can be easily compromised by inexperienced trainees or careless handling. This can result in contamination or alteration of the scene and loss of valuable evidence. Furthermore, having a large number of individuals present at a crime scene can impede an effective investigation and increase the likelihood of destroying latent evidence (Fisher 2012). Additionally, some crime scenes may not be suitable for students with mobility impairments, and students may find it challenging to keep up with the fast-paced nature of procedures and movements at a crime scene (Kader et al. 2020). While some educational institutions provide crime scene facilities for student practice, it is not practical to provide individualised investigations for a large number of students with different levels of experience and multiple scenarios in a single facility, in addition to the enormous cost of simulating several cases (Mayne and Green 2020). As a result, police academy training in investigation and forensic techniques is limited in terms of hands-on, context-based activities (Mennell 2006).

The aim of this study is to create, implement, and assess a new training system that utilises MR, which is incorporated with integrated techniques of 3D scanning to reproduce an actual based on crime scene scanned crime scenes. This extends to exploring the impacts of using this technology on the training experience from the perspective of user interaction, user experience, and overall user satisfaction. This innovative approach is expected to appeal to the younger generation of investigators as the incorporation of immersive technology in training programs would boost their engagement and interaction levels, as stated by Lindgren et al. (2016).

Quantitative research methods were utilised in this study to assess the proposed system. The questionnaire for user interaction satisfaction (QUIS) was used to measure the user satisfaction levels, and the user experience questionnaire (UEQ) was used to measure the user experience. By incorporating MR and 3D scanning technologies, trained investigators can superimpose and recreate crime scenes virtually in their actual environments, thus allowing them to learn investigation techniques and interact with the scanned scenes without any limitations to the crime scene accessibility.

This study's case examination was performed at a crime scene facility owned by the University of Winchester, which served as a simulated representation of a real crime scene. The methodology for constructing this new system is divided into two phases, as depicted in Fig. 1. The initial phase involves capturing the crime scene through 3D scanning using FARO point cloud 3D scanner X130, which captures not only the surfaces but also the textures, hues, and forensic characteristics of the scene. FARO X130 was chosen due to being privileged with the capability of covering a 130 m scanning range, in addition to the high accuracy of registration between different scans and the battery runtime of 4.5 h, which is sufficient for scanning indoor crime scenes (FARO 2021). Indoor 3D scanning necessitates specialised types of scanners that are capable of detecting walls, furniture, and blind spots, such as behind desks, under sofas, and beds. Consequently, laser scanners are commonly used for external sites, but they were utilised to scan internal venues such as scanned crime scenes (Galanakis et al. 2021). However, laser scanners have a limitation in capturing textures, hues, and characteristics during the scanning process. Therefore, to supplement this limitation, photogrammetry techniques were implemented to provide high-resolution images to be integrated into the methodology. This approach introduced an efficient method of incorporating the 3D scanning results with the photogrammetry scans to formulate a unified 3D model of the entire scene, complete with the required textures and details. The output of this phase will be considered as the input for the subsequent phase.

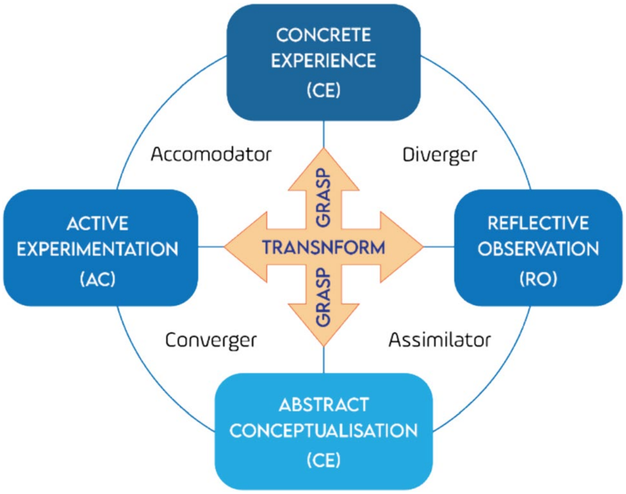


Fig. 1 The cycle of experiential learning and the fundamentals of learning styles developed by Kolb et al. (1984)

The subsequent stage in the process pertains to the construction of the MR system. The MR application has been engineered to be executed utilising the Microsoft HoloLens 2.0 headset, and it was developed using the mixed reality tool kit (MRTK) 2.0. This toolkit provides a comprehensive set of components and features to facilitate the application development process. Additionally, it allows the device, which is equipped with four cameras, to scan the physical environment, thereby providing spatial awareness that facilitates the overlay of the scanned scene onto the physical environment, thus enhancing the walking navigation experience for users (Kline et al. 2022). Consequently, the MRTK 2.0 was employed in the design and structural phases, followed by the development phase, which incorporated the use of the Unity 3D game engine, which supports Microsoft HoloLens deployment. Subsequently, the 3D-scanned scene was integrated into the project as a 3D model after its textures and features were enhanced. The system design was then constructed, and all functions and training components were conceptualised. The next phase involved incorporating MRTK 2.0 with its components to establish the functionality of the training stages. Furthermore, the user interface was designed and implemented to enable the functions of the training stages and was tested for usability. The final phase pertained to deploying the application using Microsoft Visual Studio to the headset, thus enabling testing and debugging prior to release.

The following sections are detailed as follows: Sect. 2 provides an overview of the background information and related research. Section 3 outlines the methodology employed, which encompasses the construction of the system, design principles, technologies utilised, and the system architecture. Section 4 presents the experimental results. Section 5 offers an examination of the system evaluation, which includes an analysis of the results and the outcomes of the training system.

2 Background

The concept of immersive technology aims to seamlessly integrate the physical and virtual realms, inducing a state of complete immersion (Lee et al. 2013a, 2013b). This technology encompasses various forms, including augmented reality (AR), virtual reality (VR), and MR, and has become increasingly prevalent in daily life (Suh and Prophet 2018). The education and learning sector has been impacted by AR, VR, and MR, with a proliferation of VR training applications being developed specifically for medical education (Huber et al. 2015; Fang et al. 2014; Steinberg et al. 2007). These applications facilitate haptic feedback and simulate safe environments, enabling students to practice and enhance their skills without incurring the cost of human or animal testing. In the field of engineering, AR has played a crucial role in providing electrical engineering students with a safe training experience by overlaying animated instructions onto machines (Martín-Gutiérrez et al. 2015). The realm of VR training has expanded to encompass diverse disciplines such as driver training (Bayarri et al. 1996; Ktena et al. 2015), dance training (Cai et al. 2002; Chan et al. 2010; Kyan et al. 2015), and safety training (Filigenzi et al. 2000; Sacks et al. 2013).

Recently, the utilisation of immersive technology has garnered significant attention within the field of crime scene investigation, particularly in regard to training. Through the utilisation of VR technology, researchers have been able to create simulations that offer an in-depth analysis of crime scenes, enabling them to assess and measure various dimensions and perspectives. This innovative approach opens up a plethora of opportunities to gain a more comprehensive understanding of the crime scene beyond what is possible in the physical world (Bulgakov et al. 2019). As such, the implementation of VR technology in crime scene investigation has the potential to significantly enhance the acquisition of information and lead to more insightful conclusions (Jacobs 2004).

Recent advancements in immersive technology have yielded solutions for crime scene training, such as a VR application that supports the acquisition of practical skills in crime scene investigation by providing simulations that circumvent the challenges of cost, accessibility, and size limitations of real-world crime scenes (Mayne and Green 2020). Despite the effectiveness of the VR application, the environments provided are generated by computer graphics, and some users may experience motion sickness during the training (Rebenitsch and Owen 2016). Another similar VR application employs a game-based learning approach in synthetic environments to teach criminal law (Mentzelopoulos et al. 2016). A conceptual framework has been developed to provide training for incident first responders and digital forensic investigators, and it also provides immediate performance feedback to trainees (Karabiyik et al. 2019).

2.1 Crime scene reconstruction

The utilisation of 3D Reconstruction in crime scene investigation has been a prevalent aspect of training (Meshal et al. 2023; Elhaw and Alshehhi 2024). The advent of 3D imaging techniques, such as 3D scanners, has demonstrated their efficacy in a multitude of forensic applications, as they are non-invasive and provide rapid and precise measurements. Some scanners such as FARO 3D laser scanners reaches to approximately ± 2 mm for a distance of 40 m (Flight and Ballantyne 2022; Kowalski and Skabek 2018). Thus, the results of these scans can furnish a vast amount of information pertinent to the crime scene. These imaging techniques, specifically 3D scanning and structured light scanning, have been applied in various forensic disciplines, including clinical forensic medicine (Villa et al. 2018; Kottner et al. 2017; Shamata and Thompson 2018), facial recognition (Lynnerup et al. 2009), and crime incident reconstruction (Adamczyk et al. 2017, Raneri 2018, Bolliger et al. 2012, Buck et al. 2013). Reconstruction in crime scenes took different shapes, such as the simulation approach, which involves creating the scene using computer graphics with the aid of game engines to be displayed using a VR kit (Trushchenkov et al. 2021). Other studies reviewed the reconstruction of crime scenes by integrating multiple technologies such as 3D animated graphics, motion tracking, natural language processing and computer vision to visualise the crime in courtrooms using

VR kits (Ma et al. 2010). More recent attempts have been made to reconstruct pictures of crimes in transport using AR tags for the sake of forensic training (Tolstolutsky et al. 2021). Another study used simulation methods for reconstruction purposes to be displayed on VR headsets (Ebert et al. 2014).

Despite the effectiveness of utilising 3D scanners in criminal investigation, which significantly reduces the time required for surface scanning, the final output for visual representation is significantly flawed, according to previous studies. For instance, a study has highlighted the existence of holes and discrepancies in the surfaces and textures produced by 3D scanners (Wang et al. 2019; Tredinnick et al. 2019). Furthermore, the limited ability to display the 3D models on two-dimensional screens fails to provide an immersive experience within the scanned environment. Although some studies have combined laser scans with virtual reality technologies, there remains a lack of research incorporating the use of MR headsets with mobility capabilities for the user.

2.2 Mixed reality

Mixed reality is a rising technology that presents individuals with a heightened level of interaction with the physical world in comparison to other immersive technologies such as AR and VR (Rokhsaritalemi et al. 2020).

Research has demonstrated that MR interactive environments furnish superior human outcomes in the context of crime scene investigations (Spain et al. 2018). The application of immersive technology takes various forms, including the provision of 360-degree panoramic views of three-dimensional scenes in an MR setting to facilitate remote collaboration among investigators (Teo et al. 2019). Building upon this premise, other scholars have expanded the notion of collaboration by incorporating a level of interaction utilising MR devices to assess the feasibility of such devices in the forensic sector (Rühmann et al. 2018). Previous studies have employed AR to foster collaboration among remote forensic teams, thereby promoting situational awareness (Datcu et al. 2016; Poelman et al. 2012). Scholars have also found that incorporating immersive technology into crime scenes has the potential to enrich these spaces through the utilisation of narratives and fiction (Sandvik 2010). Other studies emphasised providing in-situ annotation of the physical objects and environments via AR (Gee et al. 2010).

Several prominent authors within the field of immersive technologies have posited that MR and AR are interchangeable to some extent, with MR allowing for greater engagement with physical environments and a higher degree of interactivity (Speicher et al. 2019). From this perspective, the literature also includes studies on AR in the context of crime scene training. However, these studies have typically been designed to run on smartphones and handheld devices. For example, one AR pilot study was conducted that adopted a gaming approach to improving the forensic training experience (Leung and Blauw 2020). Other AR applications have been developed to support forensic education and involve the overlay of virtual objects onto real-world environments, using AR tags, for smartphone users (Tolstolutsky et al. 2021; Engelbrecht and Lukosch 2018). Additionally, recent studies have explored the use of markerless AR applications (Levstein and Justice 2019; Kilgus et al. 2015).

The utilisation of immersive technology has been explored in the field of crime scene investigation training, with a focus on the utilisation of AR and MR tools. Despite the potential benefits of utilising these tools, there have been relatively few studies and industrial applications that have specifically focused on using MR headsets, such as Microsoft HoloLens and Magic Leap, for crime scene training (Haque and Saleem 2020, Studio 2018). These studies have primarily utilised computer-generated simulations and 3D modelling rather than utilising 3D scanned real crime scenes.

The present investigation unveils a thorough and cohesive approach that successfully negates the challenges associated with scanning and the presence of flaws on interior surfaces and walls. This methodology leads to the creation of a highly realistic three-dimensional representation. Furthermore, the obtained 3D scene undergoes optimisation processes to enable its integration into a MR platform, thereby providing a valuable tool for training crime scene investigators.

Multiple law enforcement and policy academies, in addition to educational institutions globally, are adopting and developing virtual reality simulations for training in crime scene investigation (Cho et al. 2021; Lee and Lee 2019; Kim and Leathem 2018; Mayne and Green 2020). Despite this progress, to date, there remains a lack of simulators utilising MR technology to facilitate a more immersive and realistic experience for trainees. This includes enabling them to physically move within the scanned crime scene and interact with it in a manner that mimics actual investigation procedures.

2.3 User experience (UX)

User experience (UX) has become a crucial aspect of the design of any system or application. It refers to how a user feels and perceives while interacting with a system, product, or service. According to ISO 9241-210, UX is defined as “a person’s perceptions and responses resulting from the use and/or anticipated use of a product, system or service.” (ISO 2019). According to Hassenzahl and Tractinsky (2006), user experience is a multi-dimensional construct that consists of both pragmatic and hedonic aspects. Pragmatic aspects refer to the functional and utilitarian qualities of a product or system, while hedonic aspects relate to the emotional and aesthetic qualities that users experience. UX has several elements that are important to consider when designing a product or service. According to Lindsay and Norman (2013), the elements of UX include usability, usefulness, desirability, accessibility, credibility, and value.

The concept of user experience has been widely adopted in the field of VR and AR due to the unique nature of these technologies. VR/AR systems provide users with a highly immersive and interactive experience that differs from traditional 2D interfaces. Research has shown that the quality of visual and audio feedback (Ha et al. 2010), interactivity (Vergari et al. 2021), level of immersion (Papachristos et al. 2017), level of interaction (Ahn et al. 2017), level of control (Arifin et al. 2018), ease of use (Arrighi et al. 2021), and overall experience influence the UX in AR and VR environments. The quality of visual and audio feedback is crucial to the UX in AR and VR environments. The visual feedback must be of high quality and realistic to create a sense of presence in VR environments (Pratticò et al. 2021). Similarly, the quality of the visual feedback in AR environments determines how well the digital content is integrated with the physical world (Bermejo and Hui 2021). In a study by Gatto et al. (2022), the researchers found that users enjoyed VR environments that provided realistic visual feedback, such as detailed textures and lighting effects. Interactivity is another important factor in the UX of AR and VR environments. Users should be able to interact with virtual or digital objects in a way that is intuitive and easy to understand (Spittle et al. 2022). The level of interactivity can influence the level of immersion and sense of presence in VR environments (Morélot et al. 2021). Similarly, the level of interaction can determine how well the digital content is integrated with the physical world in AR environments (Scholz and Smith 2016).

The level of immersion is a critical factor in the UX of VR environments. Immersive VR environments can enhance the user experience by creating a sense of presence, emotional engagement, and higher memory retention (Cadet and Chainay 2020; Huang et al. 2020). In a study by Kim et al. (2020), the researchers found that users were more likely to enjoy VR experiences and retain information when they felt a sense of presence in the virtual environment. The level of control is another important factor in the UX of AR and VR environments. Users must have control over their interaction with virtual and digital objects in a way that is intuitive and easy to understand (Plantin 2021). The level of control can influence the level of immersion and sense of presence in VR environments (Servotte et al. 2020). The ease of use is another important factor in the UX of AR and VR environments. The user interface and controls must be intuitive and easy to use to ensure that users can engage effectively with the technology (Ghazwani and Smith 2020). In a study by Lee and Lee (2019) the researchers found that the UX in AR environments was better when the digital content was well integrated with the physical environment and easy to use (tom Dieck et al. 2019).

To evaluate the user experience, the User Experience Questionnaire (UEQ) is a widely used tool for measuring user experience in both AR and VR environments (Maulana et al. 2022). The UEQ consists of a standardised set of questions that aim to capture the user's overall perception of their experience and specific dimensions of user experience, such as attractiveness, perspicuity, efficiency, stimulation, novelty, and dependability (Saleh et al. 2021).

2.4 Experimental learning theory

Experiential Learning Theory (ELT) defines the process of learning as the creation of knowledge through the conversion of experience. This understanding suggests that knowledge emerges from the synthesis of grasping and transforming experiences (Kolb et al. 1984). ELT is designed to be a comprehensive adaptive process that integrates experience, perception, cognition, and behavior. Previous studies have indicated that learning styles are shaped by factors such as personality type, educational focus, career selection, current job responsibilities, and cultural influences (Kolb 2005; Kolb et al. 1984).

The model of ELT describes a cyclic journey of learning experience. To facilitate optimal learning outcomes, it is essential that the learner completes the entire learning cycle. This model delineates four stages representing two contrasting dimensions of grasping experience—concrete experience (CE) and abstract conceptualization (AC)—as well as two contrasting dimensions of transforming experience—reflective observation (RO) and active experimentation (AE). Experiential learning involves constructing knowledge by dynamically engaging with these four learning abilities. Learners must continuously decide which combination of abilities to employ in specific learning contexts. As delineated, learning unfolds in a four-stage cycle—experiencing, reflecting, thinking, and acting (refer to Fig. 1)—with the learner engaging in each stage. During the grasping experience, learners may either encounter new information by immersing themselves in the tangible, sensory aspects of the world or by engaging in abstract conceptualization. This preference for learning style influences how individuals perceive and comprehend new information—either through direct sensory experience or through symbolic representation and systematic planning. In the transforming experience, reflective observation entails observing others' involvement in the experience and reflecting on the outcomes, while active experimentation involves proactive engagement and action. Importantly, learners have the flexibility to enter the model at any stage (Kolb et al. 1984).

In the context of forensic training, CE can be provided through immersive simulations of crime scenes within the MR system, allowing trainees to engage directly with complex scenarios that mimic real-world environments. RO can potentially enable trainees to review their actions and decisions within these simulations, fostering a deeper understanding of their practical implications and outcomes. At the same time, the AC involves linking practical experiences to theoretical frameworks, helping trainees to generalize from specific instances to broader principles. AE can allow learners to apply their new knowledge in different or more complex scenarios within the MR environment, testing hypotheses and refining techniques in a risk-free setting.

Focusing specifically on AE, MR technology is uniquely positioned to facilitate this stage effectively by enabling trainees to practice and iterate on investigative techniques dynamically. This stage is critical for reinforcing learning and ensuring that trainees are not only absorbing information but are also able to apply it effectively in varied and challenging situations.

The use of MR to train investigators through the lens of ELT, with a focus on AE, ensures that learning is not only based on passive absorption of information but is an engaging, interactive process that prepares trainees for the unpredictability and complexity of real-world crime scenes. This approach not only supports the acquisition of knowledge and skills but also enhances critical thinking and adaptability—qualities essential for forensic investigators. By structuring the MR training system around these stages, particularly emphasizing the active experimentation component, we ensure that the training is comprehensive, effective, and closely aligned with the experiential learning cycle, thus maximizing the educational impact for forensic investigators.

2.5 Participatory design approach

Participatory Design Approach (PDO) is a design methodology that involves users in the design process from the beginning as co-designers throughout the design process (Van der Velden and Mörtberg 2015; Cumbo and Selwyn 2022). According to Johnson (1998), PDA is frequently acknowledged as a unique design process involving users. Three main stages are usually involved in participatory design research: Stage 1 is the "Preliminary Examination of the Task", and at this stage, designers interact with users at this early stage to learn about their work dynamics. This entails looking at the workflow, work processes, team dynamics, routines, and other aspects of the workplace in addition to the technology that is being used (Duea et al. 2022). Stage 2 is the "Procedures for Discovery", and at this stage, designers and users employ many techniques to evaluate and restructure the work organisation and to imagine the potential future workspace(Muller and Kuhn 1993). It's a chance for both sides to clarify the goals and values of the users and come to an understanding of the expected outcomes of the project. This stage's activities usually involve many users and are conducted on-site or in a designated workplace. Stage 3 is "Prototyping", and at this stage, technological prototypes customised to the ideal workplace configuration determined in the previous phase are developed collaboratively. One or more users may be involved in the prototyping process, which might happen in a lab or on-site. If the prototype works, it might potentially happen as tasks are being completed in real-time. These phases are intended to be iterative; in order to properly develop the strategy and results, they frequently cycle through several iterations. Through constant communication and feedback, this technique encourages designers and consumers to explore ideas collaboratively, improving the design (Spinuzzi 2005; Gregory 2003).

PDA was adopted in several studies that utilised immersive technologies in the training and education domains. A study used MR prototyping and PDA workshops with stakeholders to design, experience and evaluate smart environment concepts collaboratively (Yu 2017). Another study adopted PDA in VR ATM simulation training for older adults (Kopeć et al. 2019). Serious gaming was utilised alongside VR training to help learners be trained in a safe environment, and PDA was involved in the design process (Lukosch et al. 2012).

According to the literature, the potential benefit for integrating PDA in crime scenes can be predicted, as it involves educators and trainers. By its nature, PDA is connected directly to the development process, which might potentially enhance the system's relevance, practicality, and user satisfaction. By involving experts in the process, the MR system will be aligned closely with the actual needs and challenges of crime scene investigations, ensuring hands-on training experiences that officers are likely to adopt and use effectively.

Given the integration of participatory design and experiential learning theory, the following research question was formulated:

RQ: "How does the MR training system, designed through participatory methods and informed by experiential learning theory, affect user satisfaction and performance among forensic investigators?".

To address this research question, we employed two primary tools of measurement: The questionnaire on user interaction satisfaction (QUIS) and the user experience questionnaire (UEQ). The satisfaction questionnaire was designed to capture users' perceptions of the MR system's usability, relevance, and effectiveness in meeting their training needs. The UEQ, a widely recognized tool for assessing various aspects of user experience, including attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty, provided comprehensive insights into the users' overall experience with the system.

3 System architecture

The present section endeavours to elucidate the intricate composition of the MR training system and the intricacies of its inception, which is divided into two distinct stages. Stage 1, dubbed the "Capturing Crime Scene," involves the utilisation of cutting-edge techniques such as 3D scanning, photogrammetry, and post-processing to document the crime scene. In Stage 2, the "Mixed Reality Holographic Training System," the system is meticulously crafted through various phases such as structure design, implementation, integration of models into the virtual environment, user interface design utilising MRTK 2.0, and application deployment to the headset. The system was constructed based on numerous consultations with senior investigators from the Kuwait Police Academy. Support from senior investigators was received before, during, and after the development of the system. Once the system had been developed, it was trialled by experts in crime scene investigation, from whom thorough feedback was received, and this feedback refined several aspects of the system.

3.1 Stage 1–3D scanning

The pipeline normally starts with the crime scene capturing process. However, the task of obtaining realistic results from the 3D scanning of a physical environment, particularly one that contains forensic elements such as blood droplets or wall marks, presents a significant challenge (Noghabaei et al. 2019). Despite numerous endeavours to reconstruct interior crime scenes, the most formidable obstacle was capturing blind spots within confined spaces, leading to an incomplete representation of the scene (Wang et al. 2019; Jani and Johnson 2022; Mach et al. 2019). In light of these difficulties, a comprehensive review of techniques was conducted by exploring similar cases in the field of cultural heritage and through consultation with experts. As a result, a number of 3D points cloud laser scanners were shortlisted in order to attain the necessary level of detail. Ultimately, the FARO point cloud 3D scanner X130 was selected to perform the scanning process.

Securing access to an actual crime scene for the purpose of conducting a case study presents a considerable challenge, owing to the various restrictions, such as limitations imposed by law enforcement agencies, privacy considerations, and the time frame for conducting the investigation following the occurrence of the incident. In light of these complexities, utilising the Winchester University Crime Lab Facility emerged as the most feasible option. The facility is composed of two floors, with the uppermost floor accommodating two simulated murder scenes, one each representing a male and female victim, represented by mannequins placed in separate bedrooms. The lighting conditions in the rooms have been meticulously crafted to capture the essence of the crime scene, including adjusting the light balancing and illuminating the darker areas with supplementary light sources. Moreover, nine positions of the FARO have been established to cover blind spots, and checkerboard patterns have been affixed to the walls to facilitate the registration of the scans obtained during the post-processing phase, as depicted in Fig. 2.

Upon the completion of the scanning procedure, the nine scans were accurately registered, utilising the FARO SCENE software and the support of checkerboard patterns. A series of modifications were implemented in the settings to attain greater overlapping among all scans and form a single, seamless formation comprised of countless point clouds. The registration process involved comparing each pair of clusters or scanned scenes and culminated in the formation of 25 pairs of matching clusters.

The process of removing accidental and inessential point clouds from the scene was accomplished through the utilisation of Autodesk Recap Pro. This involved eliminating all inconsequential point clouds generated in error, as they would result in a distorted 3D model during the

Fig. 2 The scanners' positions in the crime scene during capturing

conversion from point clouds to a 3D polygonal model. Despite the initial 3D model being in a raw form and requiring numerous modifications, an effort was made to export it. The resulting model was of an excessive size, possessing 31 million polygons and 31,576,406 faces, making it infeasible to be utilised in any handheld or immersive headset application, regardless of the device's specifications. Additionally, when panoramic images from the photogrammetry scanning were superimposed onto the scene surfaces to assess texture quality, it was discovered that the colours were low in contrast, and there were various faults, such as gaps in textures, white spots, and areas where textures were not captured.

Photogrammetry Phase—The utilisation of photogrammetry in the process of 3D scanning has been widely recognised as a method of compensating for the inadequate generation of textures in scenes featuring forensic elements. This is due to the conventional limitations of laser scanning techniques, which frequently produce insufficient texture quality (Wang et al. 2019; Tredinnick et al. 2019). The photogrammetry approach is based on the correlation between points in the object space and corresponding image planes (Roos 1951). The process involves combining multiple images with substantial overlap and conducting mathematical computations to generate a 3-dimensional surface or model that maps a specific space (Dostal and Yamafune 2018). Studies have been conducted to explore the potential of combining photogrammetry with 3D laser scanning to produce high-quality textures (Šašak et al. 2019; Alshawabkeh et al. 2021) and in cultural heritage applications (Dostal and Yamafune 2018; Liang et al. 2018). Although photogrammetry has not yet been extensively applied in the investigation of crime scenes, its potential to enhance indoor textures and display forensic features has been explored.

The photogrammetry process necessitates the utilisation of a Digital Single Lens Reflex (DSLR) Camera, specifically the Canon EOS 5D Mark III, which boasts a robust set of hardware specifications, including a 22.3-megapixel sensor. To optimise the photographic outcome, a series of camera adjustments were performed, and the final settings were established as ISO 100, F/8 aperture, 1/400 shutter speed, and a standard lens range of 18–22 mm. While the manual focus was recommended, due to the substantial number of images required, auto-capture was elected for efficiency purposes. An external flash unit (580EX II) was deemed essential to illuminate dimly lit areas and ensure a consistent exposure balance across all captured images. flash strength was adjusted to a range of 1/8–1/16 in accordance with the existing lighting conditions. Furthermore, four external lighting units were utilised during the rapid capturing process. To guarantee accuracy during post-processing, the 'Datacolor SpyderCheckr24' was utilised to calibrate the camera and fine-tune colour adjustments. A total of 1457 images were captured from 11 distinct camera positions.

The post-processing phase endeavours to synthesise the outputs of laser scans, depicted as a three-dimensional model, with the images obtained through photogrammetry in order to fabricate an optimised and accurately textured three-dimensional representation of the scene. The procedure commences with the application of colour modifications utilising Adobe Lightroom to regulate the colour grading, tonality, and execute all necessary alterations to determine the most suitable images for the photogrammetry process. Out of the total number of images, 11.4% were excluded, and 1291 images advanced to the subsequent stage. A comprehensive investigation was conducted to assess the quality of processing and resultant models for various software programs. Recently, RealityCapture has garnered widespread recognition for its ability to effectively reconstruct textured 3D models through a process that involves the combination of clusters of images with substantial overlaps. The software employs automated procedures to construct portions of the scene through iterative alignments. However, this process is known to result in drawbacks in alignments. To address this limitation, 40 manual clusters were incorporated to bridge any missing parts of the scene. Despite the suitability of the highly overlapping images, the software ultimately failed to produce a coherent 3D model.

As a result, another iteration was carried out utilising Agi Soft Metashape. Upon importing the 3D scanned room as a 3D model in conjunction with the accompanying captured images, the alignments were accomplished in an expeditious manner. The initial generated scene was composed of 32 million faces as a raw manifestation of the model, and upon this scene, the captured images were transformed into textures for the model. Figure 3 displays a highly realistic outcome, surpassing the camera-captured images, as there are no visible gaps in the room or variations in colour. Additionally, the texture resolution is quite satisfactory and mirrors the original images. These results are comparable to recent scholarly publications that have employed similar techniques in crime scene investigation (Wang et al. 2019; Colard et al. 2013). Despite the commendable results, the model size of 31 million polygons is substantial and requires extensive processing time. Furthermore, its weight exceeds the average size of the model, particularly when utilised on portable devices such as AR or VR headsets.

Consequently, the process of reducing the raw model-decimation/compression—stage to a feasible version for scene processing commenced with the initiation of decimation. The downsizing process was implemented in a gradual manner due to the potential negative impact that a drastic reduction could have on the final model. The gradual reduction began with a model of 31 million faces and progressed incrementally to 10 million, then 5 million, 2 million, and

Fig. 3 (Left) Laser scanning and photogrammetry results, (Right) Photo of the crime scene

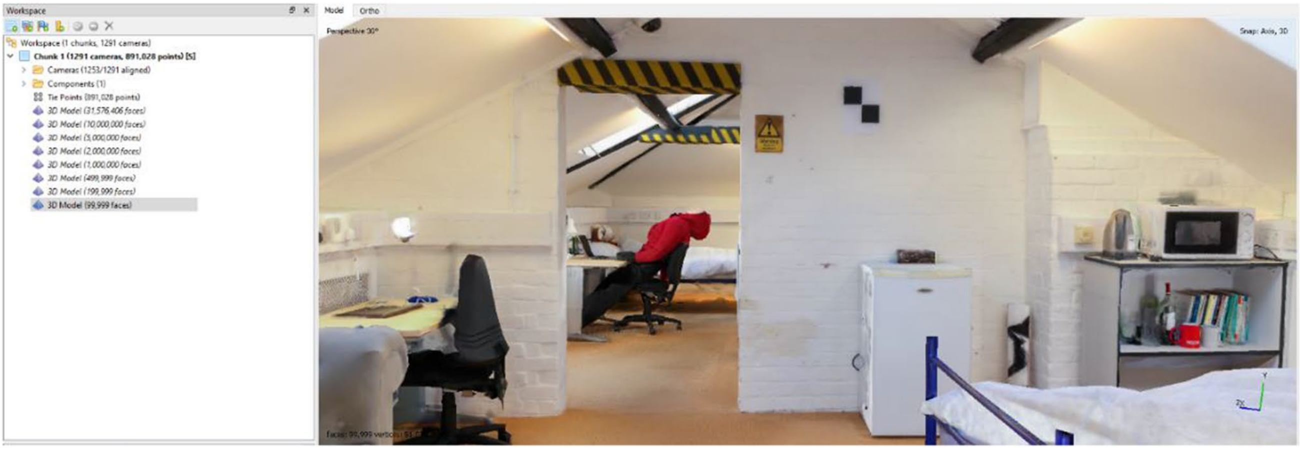


Fig. 4 Decimation/compression process in Agisoft Metashape

finally 1 million, eventually reaching a total of 99,999 faces – as depicted in Fig. 4. This approach represents a suitable compromise between the quality of the model, the resolution of the textures, and the processing capabilities of portable devices, including and MR devices.

In the realm of post-processing, it was observed that despite the highly realistic visual representation of the crime scene produced, certain inconsistencies were present, such as disparities in surface level and the existence of voids on the surfaces. These anomalies were primarily located in areas that were overlooked during the 3D scanning and photogrammetry processes. Therefore, it is imperative to maintain the integrity of crime evidence by carefully modifying the structure or texture of the room. Subsequently, minimal modifications were carried out on the model utilising Autodesk 3Ds Max to fix surface irregularities and fill any gaps in blind spots such as under beds or behind sofas. These modifications were performed with caution to ensure that the fundamental measurements of the scene were not altered.

In order to facilitate training and receive guidance from seasoned forensic experts, certain digital brush paintings were superimposed upon the criminal settings to form a sequence of indicia and to imitate the actual crime scenes. The additional artificial clues encompass but are not limited to imbuing a criminal implement with blood, blood droplets, and biometric information onto polished surfaces, as presented in Fig. 5.

3.2 Stage 2—MR system development

This stage encompasses the elaboration of the structural design of the MR application, the progression of the development cycle, the integration of models into a virtual environment, the implementation of user interfaces utilising MRTK 2.0, the deployment of the application onto the headset, the evaluation and rectification of defects, and ultimately, a reiteration of the testing and bug fixing process.

Apparatus- The Microsoft HoloLens 2 is a self-contained MR headset that enables the overlay of digital content onto the real world. It features a transparent visor, sensors, cameras, and a high-resolution display. The HoloLens 2 is equipped with a powerful custom holographic processing

Fig. 5 Adding crime effects in the crime scene digitally

unit (HPU) and runs on the Windows MR platform. The utilisation of the HoloLens 2 offers an immersive and interactive experience for trainees, allowing them to explore and interact with virtual crime scenes.

System Design—the PDA was integrated to construct the system design with extensive involvement of the senior investigators. As in phase 1, the design team, alongside the senior investigator, delved deeply into the unique dynamics of police investigative work to explore the initial exploration of the investigation practices. This phase was crucial for understanding the technology currently in use and the broader operational context—including workflow, procedural nuances, team interactions, and routine activities typical of investigative work. This comprehensive understanding allowed the research and design team to identify critical areas where the MR application could enhance training and operational efficiency, setting a solid foundation for the application's development. In the next phase, the collaboration between the design team and the senior investigators focused on redefining and optimizing the workflow for investigative training as part of the discovery process. Through a series of workshops and brainstorming sessions, which often took place in settings that simulated real investigative environments, both parties were able to articulate and align on the core objectives and values that the MR system should support. This phase was instrumental in sketching a detailed blueprint of what the future training environment should encompass, ensuring that the system would meet the realistic demands of crime scene investigations and align with the professional growth goals of the investigators. Prototyping was the third phase, a dynamic and iterative phase in which the initial designs were brought to life. The senior investigators played a critical role in this stage, testing and providing feedback on various prototype iterations. This collaborative development occurred in lab settings and directly in simulated crime scenes to ensure that the prototype functioned effectively under realistic conditions. The iterative testing and refinement process helped fine-tune the MR application, ensuring that the technology was functional, intuitive, and directly beneficial for training purposes. This stage was crucial for integrating real-world applicability into the MR system, allowing for adjustments that reflect actual investigative challenges and scenarios.

Therefore, the structural design of the system was meticulously built in its formative stages to be in compliance with Microsoft HoloLens 2.0, the MR headset that will be utilised in the investigation training. The objective is to overlay the virtual crime scene in a spacious environment that can be placed upon the physical surroundings. The system's structure divides the training into four crucial phases, specifically: look around, add markers, check victims, and guess the criminal, as depicted in Fig. 6. This will be followed by an optional station that emulates the crime scene using animated virtual avatars. The training's design was formulated in accordance with the standard framework, as demonstrated through continual collaboration with a group of experts who specialise experts specialising in serious investigations.

Development—The Microsoft HoloLens team has introduced a powerful toolkit known as MRTK 2.0, which constitutes a comprehensive collection of scripts that facilitate the creation of various functionalities. The utilisation of MRTK is facilitated by its integration with the unity game engine, enabling developers to employ the C# scripting language in the construction of the system. The deployment of application files into the headset is achieved through the utilisation of Microsoft Visual Studio.

Implementation—The implementation of 3D models within a virtual environment entailed the transfer of the 3D model and its accompanying set of texture images to Unity. The 3D model was extracted from 3Ds Max, and the textures were from adobe substance painter. A significant challenge in this process was determining the optimal shader to display the texturing accurately, as the 'Mixed Reality Toolkit' shader produced a partially transparent outcome.

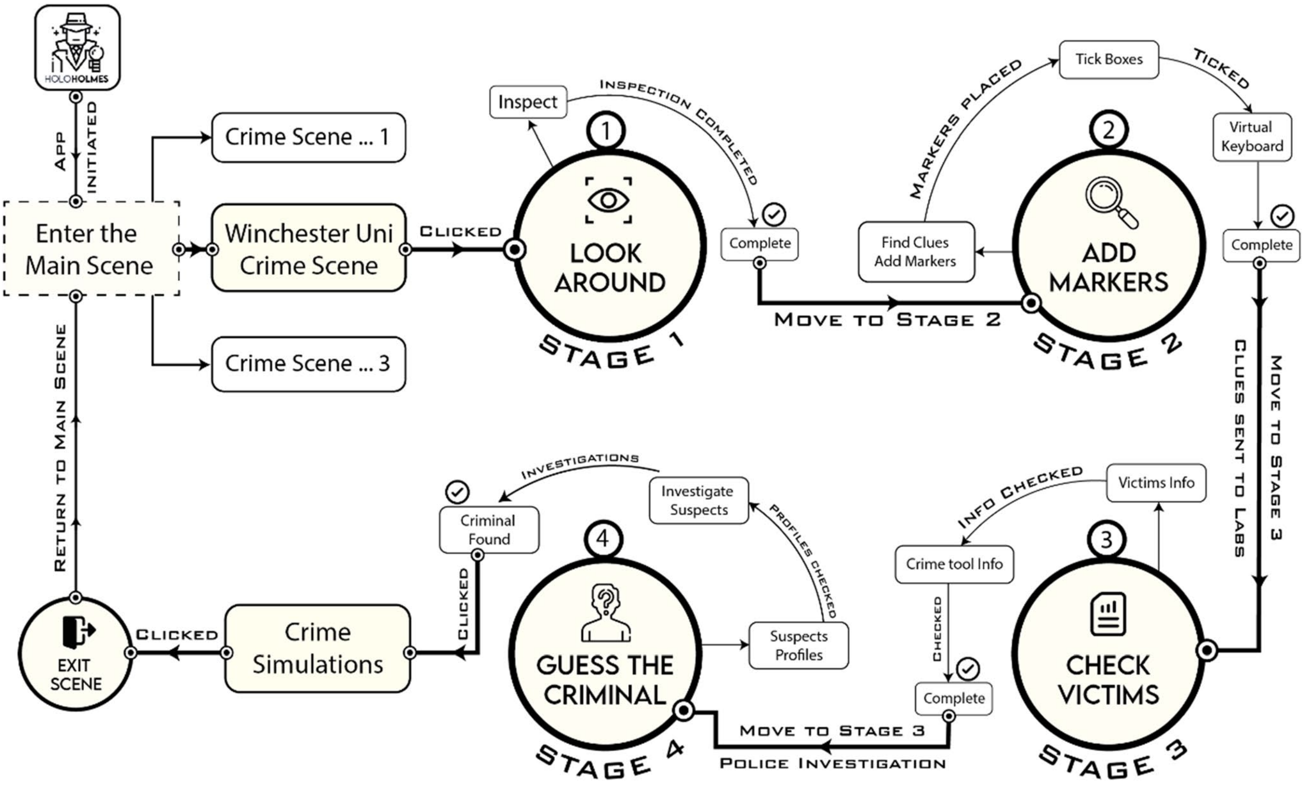
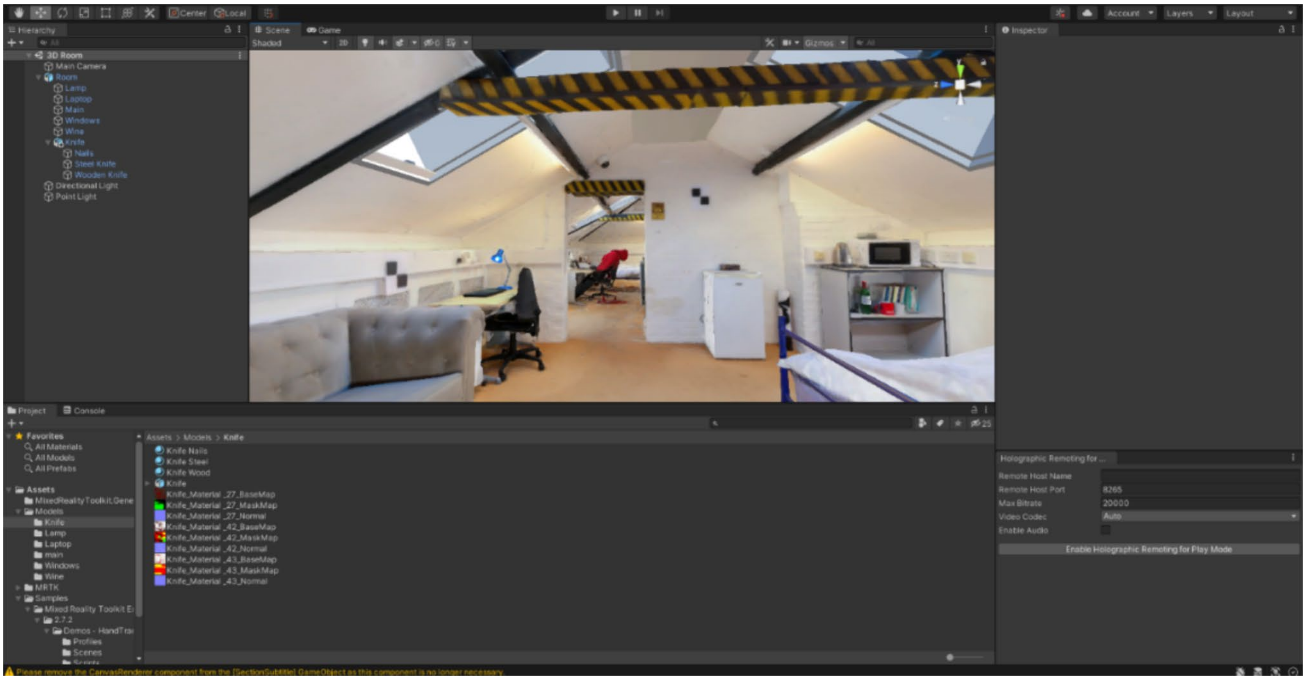


Fig. 6 System design



Remote Host Name
Remote Host Port 8265
Max Bitrate 20000
Video Codec Auto
Enable Audio ☐

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Please remove the CanvasRenderer component from the [SectionSubtitle] GameObject as this component is no longer necessary.
```

Fig. 7 Virtual crime scene in unity after adding shaders

Ultimately, the ‘Unlit/Texture’ shader was deemed the most suitable option despite its lack of surface shadow casting capabilities—as depicted in Fig. 7. Incorporating the virtual crime scene into the physical environment required adjusting the scaling to align the actual room size with the physical environment and ensuring the two were on the same level. To minimise any potential safety hazards, it is preferable to overlay the visuals onto an environment that is free of obstacles.

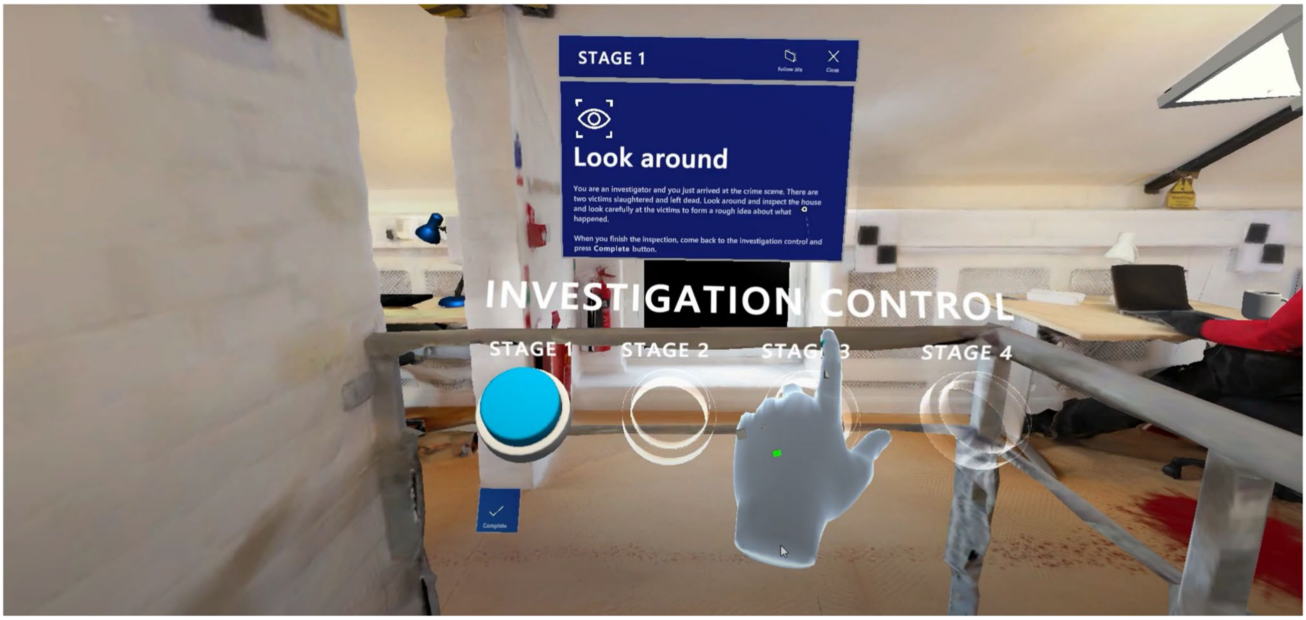
UI Design—The MRTK serves as an aid for the creation of MR applications by providing an array of components and functionalities. One of its salient features is the ability to construct spatially aware floating user interfaces through the utilisation of designated building blocks for hand-air tapping interactions. The MRTK 2.0 further facilitates the creation of touch and gesture-based buttons for object interactions, a capability that has been heightened with the integration of advanced AI algorithms in the HoloLens 2.0 to recognise natural hand gestures. Consequently, these tools empower developers to construct interactive visual representations of system user interfaces.

3.2.1 System scenario

First Stage: The objective of the “Look Around” is to acclimate the trainee to the criminal site and elicit an initial criminal evaluation. This aligns with the concept of “incident response”, as propounded by Beebe and Clark (2005) in their distinctive investigatory framework. An essential competency for investigators is the ability to scrutinise the evidence and identify any changes or movable objects present at the scene. The purpose of this phase is to cultivate these investigative techniques. The trainee should be equipped to address the following questions: How did the perpetrator gain access to the scene? What transpired? Who are the casualties? Where were they killed? Was any criminal instrument left behind? Are there any recognisable bloodstains? As depicted in Fig. 8, the user will be directed to the investigation control once the scene examination commences. The system is constructed in a modular fashion, where the completion of each phase unlocks the subsequent one.

Second Stage: The “Add Markers” stage focuses on a crucial aspect of the investigation, specifically, data collection. This is in alignment with the investigative framework presented by Beebe and Clark. The stage is designed such that a number of clues are placed in both the rooms and the main task. A floating board with yellow numbered tags is presented to the user, allowing them to virtually pick up the clues and place them on potential evidence. The tags automatically generate themselves, with each subsequent tag carrying an incremented number. There are 24 tags present in the current scene, and a board with checkboxes is provided to enable the trainee to list all potential clues. Additionally, a virtual keyboard is located in the corner for the purpose of taking notes for other investigators. Completion of this stage is a pre-requisite for unlocking the next stage, as depicted in Fig. 9.

Third Stage: The “Check Victims” stage aligns with the concepts of “Data Analysis” and “Finding Representation” as outlined in the specialised investigation framework proposed by Beebe and Clark (2005). This stage primarily entailed an analysis of the biometric evidence submitted to



You are an investigator and you just arrived at the crime scene. There are two victims slaughtered and left dead. Look around and inspect the house and look carefully at the victims to form a rough idea about what happened.

When you finish the inspection, come back to the investigation control and press **Complete** button.

Fig. 8 First stage—“Look Around”

Place Markers and Tick Boxes

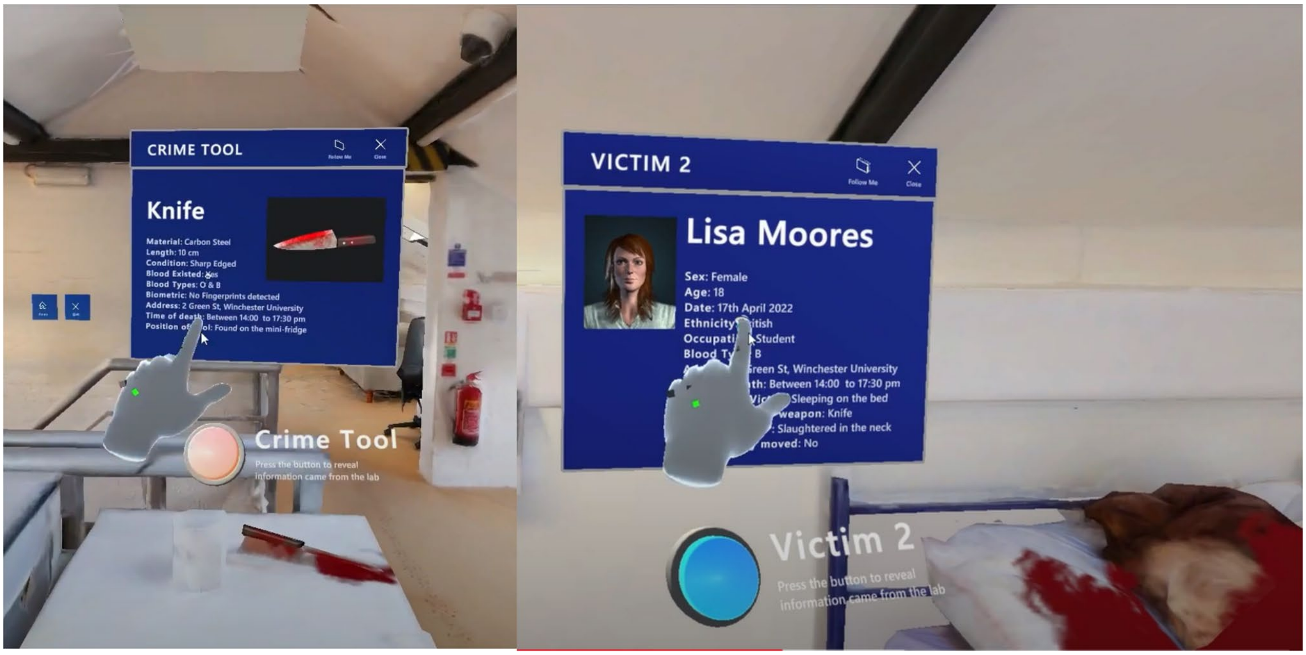
☐ Blood Evidence 1
☐ Blood Evidence 2
☐ Blood Evidence 3
☐ Fingerprint 1
☐ Fingerprint 2
☐ Fingerprint 3
☐ Fingerprint 4
☐ Fingerprint 5
☐ Crime Tool
☐ Movable Object 1
☐ Movable Object 2
☐ Movable Object 3
☐ Movable Object 4
☐ Violence Evidence 1
☐ Violence Evidence 2
☐ Violence Evidence 3

Find Clues & Add Markers
Grab the yellow markers and place it next to any potential crime evidencer

Fig. 9 Second stage—“Adding Markers”

the laboratory and received in response, serving as a source of information for the trainee. In accordance with this, the communicative board provides direction for the trainee to examine the locations where the collected evidence has been found in order to scrutinise the reports submitted by the forensic team. At this stage, the trainee has the opportunity to ascertain the identity of the victims. The informative board is meticulously crafted to accompany the investigator in their movements, thereby facilitating the process of linking clues together to construct a plausible scenario—as depicted in Fig. 10.

Fourth Stage: The stage referred to as the “Define the Criminal” is correspondingly mapped to the “incident Closure” phase within the framework articulated by Beebe



CRIME TOOL

Knife

Material: Carbon Steel
Length: 10 cm
Condition: Sharp Edged
Blood Existed: Yes
Blood Types: O & B
Biometric: No Fingerprints detected
Address: 2 Green St, Winchester University
Time of death: Between 14:00 to 17:30 pm
Position of ol: Found on the mini-fridge

Crime Tool
Press the button to reveal information came from the lab

VICTIM 2

Lisa Moores

Sex: Female
Age: 18
Date: 17th April 2022
Ethnicity itish
Occupati Student
Blood Ty B
reen St, Winchester University
th: Between 14:00 to 17:30 pm
Vic Sleeping on the bed
weapon: Knife
: Slaughtered in the neck
moved: No

Victim 2
Press the button to reveal information came from the lab

Fig. 10 Third stage—“Check Victims”

and Clark (2005). This stage serves to enhance the competencies of the investigative trainee by facilitating the process of determining the culpable party from among multiple subjects and police intelligence when traditional evidence analysis has proven insufficient. Furthermore, this stage seeks to continue the investigation by presenting data regarding all suspects who possess biometric markers at the crime scene. The stage has been designed to incorporate a gamified aspect through the utilisation of an innovative tool known as "Guess Who is the Criminal",—as depicted in Fig. 11. This tool provides users with access to the profiles of all suspects and the ability to conduct further investigations by examining CCTV footage, ultimately aiding in the identification of the most likely criminal. In terms of user experience, the buttons within the holographic user interface have been visually and interactionally differentiated, as well as distinguished by unique audio outputs, to clearly distinguish between investigative functions and suspect information retrieval.

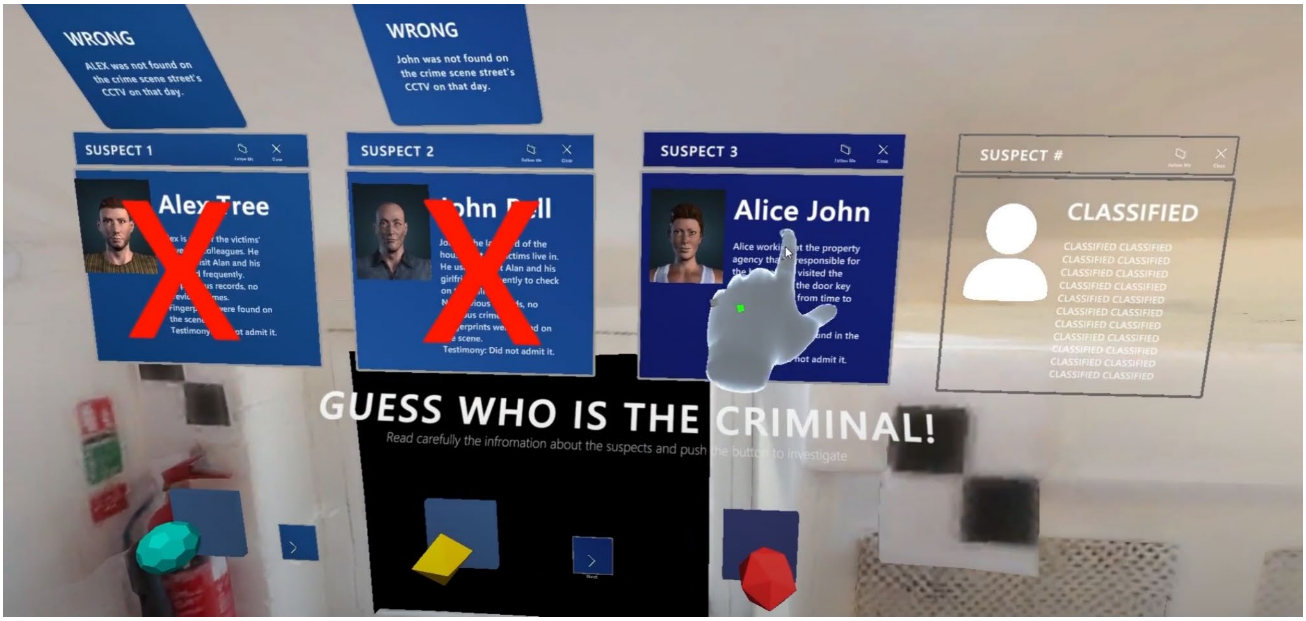
Simulation Stage: As part of standard investigatory procedures, it is imperative to simulate the criminal's actions following detainment, as this can assist in the recollection of events and the correlation of all evidence with the perpetrating actions (Carmel et al. 2003). In order to amalgamate all the pertinent information effectively, it is of utmost importance to present an animated simulation of the crime once it has been resolved. Subsequently, upon resolution of the task, the user can initiate the visual representation of a 3D avatar character at the crime scene, who will enact the crime and interact with the virtual environment – as demonstrated in Fig. 12.

4 Methodology

An exploratory evaluation was carried out to evaluate the interactivity and user experience, including the user interface of the holographic crime scene training system. The examination aimed to determine the level of satisfaction among the designated user demographic, which was comprised of trained investigators in the form of police academy students, as part of their educational curriculum.

4.1 Participants

The present study has received ethical clearance from the Ethical Committee of Liverpool John Moores University. Participants for the study will be sourced from two distinct groups. The first group comprises students of the Kuwait Police Academy, ranging in age from 18 to 50 years, who are considered young investigators employing conventional crime investigation methods. The study will commence with these participants' training on using Microsoft HoloLens 2.0, an MR headset, in an expansive space or a vacant classroom. This initial stage is estimated to take approximately 10 min. Participants will be instructed to don the headset and visualise a virtual crime scene, after which they will be required to inspect the scene and gather virtual evidence, such as blood traces, crime tools, and objects bearing fingerprints, before transmitting the biometric evidence to a virtual laboratory. The participants will then be tasked with solving the case and identifying the criminal from among multiple suspects, with an estimated time frame of 20 min.



WRONG

ALEX was not found on the crime scene street's CCTV on that day.

WRONG

John was not found on the crime scene street's CCTV on that day.

GUESS WHO IS THE CRIMINAL!

Read carefully the information about the suspects and push the button to investigate

Fig. 11 Fourth stage—"Guess Who is the Criminal"

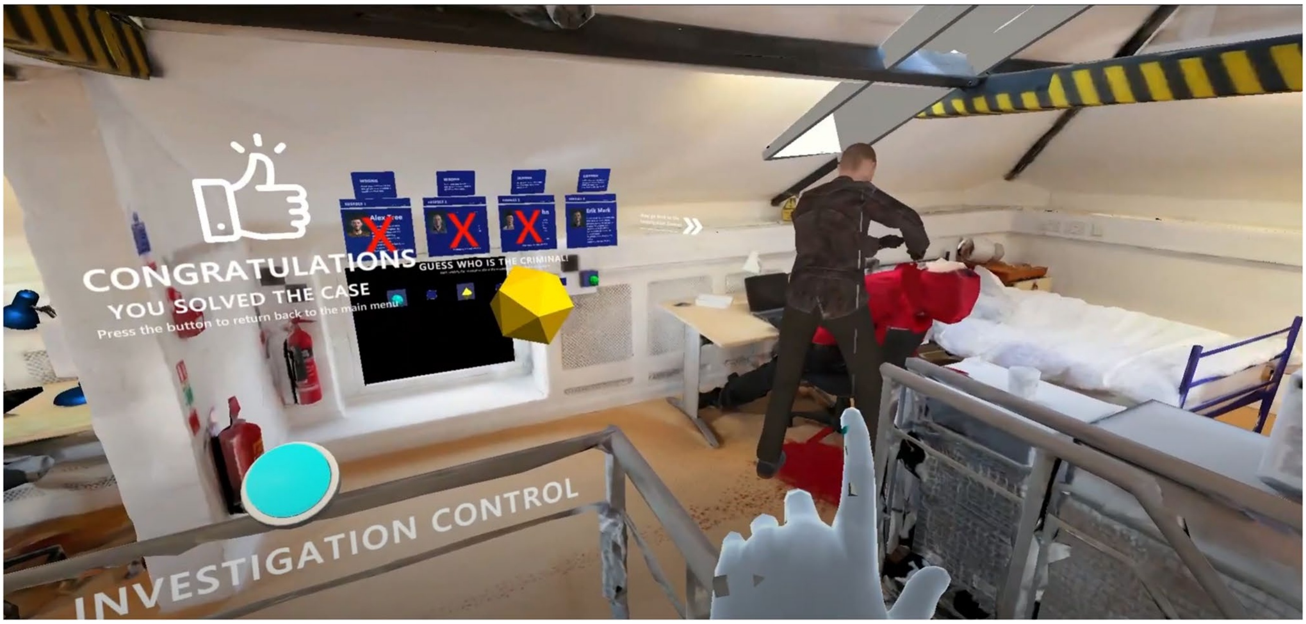


Fig. 12 Crime simulation

Following completion of the task, participants will be required to fill out two questionnaires: The questionnaire for user interaction satisfaction (QUIS) and the user experience questionnaire (UEQ). QUIS assesses the system's user interaction satisfaction, while UEQ assesses the user experience satisfaction.

The students were formally notified through electronic correspondence to participate in the trial day. A reservation protocol was implemented to allocate each individual a period of 20–30 min. The trial system was put into effect and underwent experimentation with numerous participants over the course of 4 consecutive weeks. Prior to commencement, all participants were required to execute a waiver of consent, following which they received instructions on the utilisation of the device and the MR exploration system. Additionally, the survey instrument will be transcribed into Arabic, the prevalent language in Kuwait, and the interview queries will be rendered into the same language for the purpose of recording the responses digitally for subsequent transcription and translation.

4.2 Methods

4.2.1 Questionnaire for user interaction satisfaction—QUIS

QUIS is a widely used instrument for measuring user satisfaction with computer-based systems, and it was initially developed by (Chin et al. 1988b). The QUIS has been extensively validated and used in various contexts, including information systems, human–computer interaction, and usability engineering (Chin et al. 1988a; Norman and Shneiderman 1989). QUIS is a standardised questionnaire that assesses user satisfaction with a range of factors, including system responsiveness, aesthetic appeal, and overall usability (Hornbæk 2006).

Several studies have used the QUIS to evaluate user satisfaction in AR and VR systems. For example, a study by Su et al. (2020) used the QUIS to assess the user interface and VR experience in the context of e-commerce. Also, Xue et al. (2019) used this tool to evaluate user satisfaction with an AR-based training system. Similarly, Altarteer et al. (2013) used it to assess user satisfaction with an interactive VR shopping system.

In this study, the questionnaire QUIS was designed to measure overall system satisfaction and five specific interface factors, which include visuals and holograms, terminology and system information feedback, learning factors, and system capabilities. This covers the desired aspect of the study requirements. The questionnaire was comprised of 44 QUIS items with a scale mapped to numeric values of 1–9 as it was built on the study of Chin et al. (1988b) and then created accordingly:

- Holograms: The user's experience of perceiving the holographic text, panels, spatial design and arrangements in the field of view.
- Terminology and system information: The user's understanding of the system's commands and terms regarding the interaction with the investigation tasks.
- Learning: The user's ability to learn how to operate the system and explore its features.

- System capabilities: The user's experience with the system's proficiency and effectiveness.
- General impressions: The user's satisfaction with the overall system.

To evaluate user interaction satisfaction, the reliability, consistency, and validity were assessed using Cronbach's alpha for each questionnaire item and means, and standard deviations were calculated to understand response tendencies. The reliability of the QUIS data was further verified through Levene's test for equality of variances, followed by independent samples T-tests to examine differences between groups, particularly in relation to previous AR/VR headset experiences. The significance level was set at $p<0.05$. Additionally, two-sample T-tests were conducted to explore how prior experiences with immersive technologies might influence user satisfaction. This streamlined approach ensures the study's findings are both robust and replicable, providing clear insights into user interaction satisfaction in the context of AR/VR technologies.

4.2.2 User experience questionnaire—UEQ

UEQ is a widely used tool for evaluating the overall user experience (UX), including the quality and effectiveness of a product or service from the perspective of the user. Developed by (Laugwitz et al. 2008), the UEQ consists of a set of standardised questions designed to measure various aspects of the user experience, including usability, functionality, aesthetics, and emotional response.

The UEQ has been shown to be a reliable and valid measure of user experience, with high levels of consistency and correlation with other measures of user satisfaction (Schrepp et al. 2014a; Schrepp 2015; Paramitha et al. 2018). Additionally, the questionnaire has been used in a variety of contexts, including web design (Hinderks et al. 2019), software development (Zhu et al. 2022), and AR and VR applications (Su et al. 2020; Somrak et al. 2019), making it a versatile and adaptable tool for researchers and practitioners alike (Somrak et al. 2021).

One of the key strengths of the UEQ is its focus on the subjective experience of the user. Unlike other measures of user experience, which often rely on objective metrics such as task completion time or error rates, the UEQ asks users to self-report their feelings and impressions about the product or service being evaluated (Laugwitz et al. 2008). This allows researchers to capture the full range of user experiences, including both positive and negative emotions, and to identify areas where the software or system design may be lacking from the user's perspective (Schrepp et al. 2014a; Schrepp 2015; Paramitha et al. 2018).

The UEQ was employed to evaluate user experience, comprising 26 items that were rated using the 7-point Likert scale to measure six aspects of user experience (Laugwitz et al. 2008):

- *Attractiveness* How appealing is the product in terms of its overall appearance? Do users have positive or negative feelings about it?
- *Perspicuity* Can the product be easily learned and familiarised with?
- *Efficiency* Is it possible for users to complete their tasks without unnecessary effort?
- *Dependability* Is the user able to exercise control over the interaction?
- *Stimulation* Does using the application generate excitement and motivation while using it?
- *Novelty* Is the product innovative and able to generate interest in users through its creative features?

The items are measured on a scale from -3 to 3, with higher scores indicating more agreement with the scales and lower scores indicating more disagreement. The most negative answer is represented by -3, a neutral answer is represented by 0, and the most positive answer is represented by 3. Scores above one are considered positive evaluations. Attractiveness is a pure measure of positive or negative value, while Perspicuity, Efficiency, and Dependability are pragmatic quality aspects (goal-directed). At the same time, Stimulation and Novelty are hedonic quality aspects (not goal-directed).

A detailed approach was employed to analyse the UEQ using the aforementioned 6-point scale. This involved calculating the mean and standard deviation to understand response trends and variability, respectively. Confidence levels were quantified through confidence intervals, while Cronbach's alpha was used to assess the internal consistency of the UEQ dimensions. This rigorous analytical framework underpinned the robust evaluation and discussion of user experience in our research.

5 Results

5.1 Participants demographic

The participants from this study were 44 students from the Police academy in Kuwait who are considered trained investigators. The participants were from various age groups: 25 (56.8%) of them were aged 18–25 years, 15 (34.1%) were from the 26 to 35-year age group, and only 4 (9.1%) were aged 36–60 years. Table 1 showcases the breakdown of the gender groups, as male participants were slightly over females, with percentages of 56.8% and 43.2%, respectively. Most of the participants have generic knowledge of XR technologies, with a percentage of 70.5%. In contrast,

Table 1 Data on the participants' demographic

Variables	Question	*N*	%
Age	18–25	25	56.8
	26–35	15	34.1
	36–60	4	09.1
Gender	Male	25	56.8
	Female	19	43.2
Knowledge of XR technology (AR, VR & MR)	Yes	31	70.5
	No	13	29.5
Used AR or VR apps/solutions generally	Yes	26	59.1
	No	18	40.9
Previous Experience with AR/VR headsets	Yes	20	45.5
	No	24	54.5
Willing to use the system if it can provide complete training	Yes	33	75.0
	No	11	25.0

Table 2 Data reliability analysis of QUIS

Construct	*N*	Cronbach's Alpha
Holograms	44	0.77
Terminology and system information	44	0.70
Learning	44	0.71
System capabilities	44	0.73
Overall Impressions	44	0.72

the group that actually used AR/VR applications or solutions is slightly more than those that have not been exposed to this experience, with percentages of 59.1% and 40.9%, respectively. However, students who had experience using AR/VR headsets were less than students who had not, with a slight difference, as their percentages were 45.5% and 54.5%, respectively. Interestingly, a high percentage of students showed a willingness to use the system if it can support the entire practical program, a percentage of 75%. This is considering the system used as a demo that includes the non-comprehensive part of the investigation training.

5.2 QUIS results

To ensure the credibility of the data collected, the reliability test has to be conducted to judge the consistency of the responses in the questionnaire adopted for this study. According to Nunnally and Bernstein 3rd (1994), sufficient and satisfactory data has to score over 0.7 for Cronbach's alpha measurements. Table 2 reveals the findings of the reliability analysis, indicating that the QUIS of the study demonstrated a satisfactory level of reliability, as evidenced by its Cronbach's alpha score exceeding 0.7. The five constructs of the QUIS, namely holograms, terminology and system information, learning, system capabilities, and overall impressions of the system, demonstrated a degree of consistency and reliability, which suggests that the credibility of the questionnaire is reasonably good. The questionnaire used the Likert 9-point scale. The results of Table 2 indicate that the participant's satisfaction with the five constructs is quite high, with an average score of around 7. In particular, the hologram construct had the highest score, indicating that participants had a positive satisfaction with the visual components of the system's user experience.

In terms of the descriptive analysis, as demonstrated in Fig. 13, the mean values for the five constructs ranged from

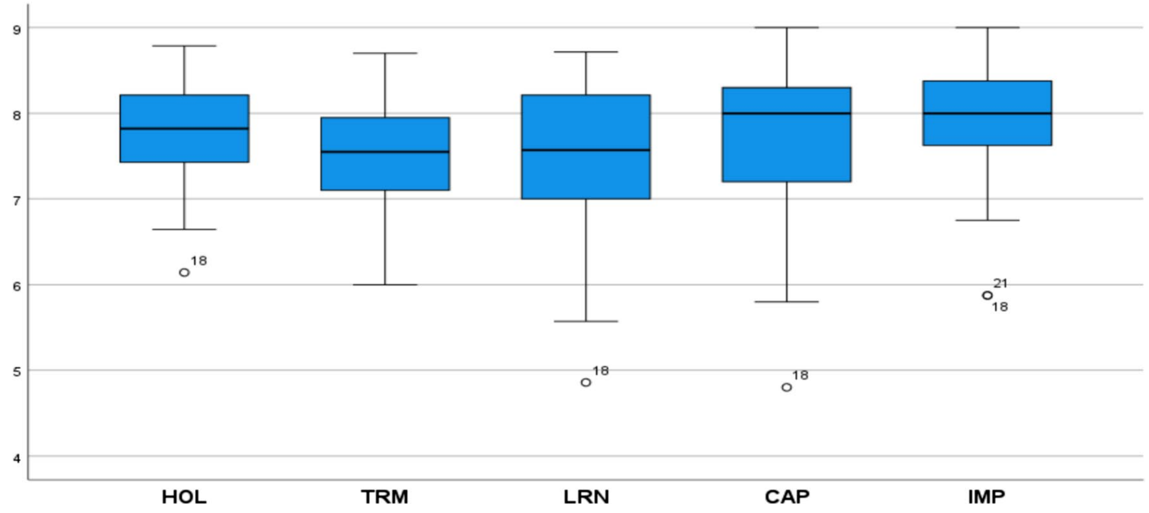


Fig. 13 Mean ranges for the main five constructs for QUIS *HOL = holograms, TRM = terminology and system information; LRN, learning; CAP = system capabilities; IMP, overall impressions

Table 3 QUIS Statistical analysis

Construct	Item	*N*	Mean	SD	Construct mean	Construct SD
Holograms	Appearance of characters and fonts in the displayed holograms	44	7.88	1.074	7.74	0.61
	Contrast of characters with the background	44	7.91	.895		
	Animated visuals make tasks easier (e.g., hand pushing button)	44	7.79	1.206		
	Differentiating button colours	44	8.09	1.065		
	Sound effects while doing hand interactions	44	7.63	1.328		
	Number of visuals displayed spatially in front of the user	44	7.56	1.098		
	Sequence of Stages	44	7.74	1.071		
	Going back to the main Scene	44	7.84	1.252		
	Knowing where you are in the task (what you have done. and what you need yet to do)	44	7.60	1.256		
	UI Buttons are easy to select	44	7.28	1.533		
	Buttons are easy to find	44	7.77	1.212		
	Button selection area size	44	7.74	1.274		
	Seeing selection lines (when performing longer air taps)	44	7.84	1.214		
	Knowing whether an item is selected	44	7.74	1.432		
Terminology and system information	Use of terms throughout the system (e.g., hold, move, click …etc.)	44	7.75	1.278	7.51	0.64
	Button describes its functions (Button labels)	44	7.59	1.207		
	Messages (feedback) which appear on the screen	44	7.41	1.263		
	Location of messages on the screen	44	7.32	1.235		
	Guided messages through stages of investigations	44	7.57	1.169		
	Visuals and buttons clarify where you are in the investigation process	44	7.50	1.389		
	The flow between stages of investigations	44	7.80	1.250		
	Instructions to the user for commands or choices	44	7.48	1.229		
	Instructions for hand interactions	44	7.16	1.256		
	System keeps you informed about what it is doing	44	7.59	1.168		
Learning	Learning to operate the system	44	7.59	1.352	7.41	0.91
	Learning advanced features	44	7.27	1.575		
	Time to learn to use the system	44	7.20	1.720		
	Exploration of features by trial and error	44	7.27	1.590		
	Exploration of features	44	7.59	1.187		
	Tasks can be performed in a straight-forward manner	44	7.41	1.499		
	Number of steps per task	44	7.57	1.546		
System capabilities	System speed	44	7.59	1.187	7.67	0.86
	System response time for most operations	44	7.66	1.219		
	Ability to undo what you just did	44	7.68	1.177		
	The needs of both experienced and inexperienced users are taken into consideration	44	7.50	1.486		
	Perceived ease-of-use of system	44	7.93	1.108		
Overall impressions	Floating panels are aesthetically pleasing	44	7.84	1.180	7.93	0.70
	UI designs and layout are attractive	44	7.61	1.385		
	Use of colour combinations	44	7.64	1.658		
	System is impressive	44	7.77	1.750		
	Such a system in a crime investigation training would be useful	44	8.18	.870		
	System is fun to use	44	8.34	.805		
	System maintains one’s interest	44	8.11	.895		
	System would remain interesting in the future with more expansion	44	8.00	1.012		

7.41 to 7.93, considering the learning construct is the lowest, and the overall impression is the highest. The subsequent step involves evaluating the analysis of each aspect presented in the questionnaire. Based on the outcomes reported in Table 3, the majority of participants expressed a satisfaction rating of approximately 7. Specifically, regarding the system's capabilities, participants reported a satisfaction rating of over 8 in five aspects. Satisfaction scored 8.34 for "system is fun to use," indicating that students enjoy the training system while practising. An aspect of "Such a system in a crime investigation training would be useful" scored 8.18 for the "Overall impression" construct, which indicates the satisfaction of usefulness as a training tool. The following aspect was rated as 8.11 for "Maintain someone's interest". Moreover, "Differentiating button colours" for "Holograms" with a score of 8.09 indicates satisfaction with the User Interface aspects. The last aspect that scored eight and above was "System would remain interesting in the future with more expansion" for "Overall impressions", indicating the user are willing to see more practical training modules to enhance their skills and to indicate the willingness for future use.

Nonetheless, participants encountered difficulty in responding to two questions, with satisfaction levels ranging from 7.1 to 7.2. These questions pertain to "Instructions for hand interactions" for "Terminology and System Information" and "Time to learn to use the system" for "learning".

The utilisation of a two-sample *T*-test is commonly employed to compare the mean of two samples for statistically significant disparities. This investigation employed the two-sample *T*-test to analyse five constructs against the responses of the gender group and the group that has experience using AR/VR headsets. The outcome of each *T*-test was as follows: statistical analysis of gender, two-sample *T*-testing—demonstrated in Table 4, and statistical analysis of previous experience on AR/VR headsets—detailed in Table 5. The initial analysis was based on gender, male and female students. The results presented in Table 4 indicate that with regard to satisfaction, both male and female participants reported an average satisfaction rating of approximately 7,

Table 4 Data reliability analysis of QUIS

Construct	*Gender*	*N*	Mean	SD	Levene's test sig	*T*-test	
						T value	Sig. (two-tailed)
Holograms	Male	25	7.73	0.13	0.47	−0.13	0.891
	Female	19	7.76	0.13			
Terminology and system information	Male	25	7.52	0.15	0.21	0.09	0.926
	Female	19	7.50	0.11			
Learning	Male	25	7.45	0.19	0.62	0.29	0.769
	Female	19	7.36	0.19			
System capabilities	Male	25	7.71	0.21	0.10	0.34	0.735
	Female	19	7.62	0.14			
Overall impressions	Male	25	7.59	0.14	0.04	−4.55	< 0.001
	Female	19	8.39	0.07			

*p value < 0.05

Table 5 The analysis of Two-sample and *T* testing of the previous experience with AR/VR headsets

Construct	Previous experience with AR/VR headsets	*N*	Mean	SD	Levene's test sig	*T*-test	
						T value	Sig. (two-tailed)
Holograms	Yes	20	8.01	0.10	0.41	3.31	0.002
	No	24	7.45	0.12			
Terminology and system information	No	20	7.70	0.14	0.59	1.60	0.116
	Yes	24	7.40	0.12			
Learning	No	20	8.10	0.10	0.02	6.13	< 0.001
	Yes	24	6.84	0.17			
System capabilities	No	20	7.91	0.17	0.47	1.93	0.061
	Yes	24	7.39	0.20			
Overall impressions	No	20	8.13	0.09	0.01	1.82	0.076
	Yes	24	7.75	0.18			

*p value < 0.05

and the data were nearly identical. With the exception of the perceived response of female participants on the overall impressions, with a score of 8.39 compared to male participants, who scored 7.59. Male participants recorded slightly higher ratings in the other constructs, such as system capabilities and learning. Nonetheless, overall, there were no significant disparities in satisfaction between both genders in other measured constructs.

Levene's test was conducted to assess the significance of different constructs. The test yielded the following results: the *p*-value was 0.47 for holograms, 0.21 for terminology and system information, 0.62 for learning and 0.10 for system capabilities. However, *p*-value for overall impressions of the system was 0.04, which is considered significant as the $p < 0.05$. This indicates that the correlation between females' usage of this system is significant. The results of the other four constructs had *p*-values greater than 0.05, indicating that there was no significant difference among them, indicating homogeneity of variance.

The following analysis to be demonstrated is the *T*-test analysis, as it shows the significance (two-tailed) of the different constructs. The holograms construct has a *p* value of 0.89, terminology and system information has a *p* value of 0.92, and learning has a *p* value of 0.76 and system capabilities have a *p* value of 0.73. However, the overall impressions of the system have a *p* value of < 0.001, confirming the significant correlation between the usage of the system by female students and the positive overall impressions. All the other four constructs had *p* values greater than 0.05, which is not significant, and therefore, the null hypothesis was not rejected. This indicates that there is no significant difference in gender except in the overall impressions that are affected by female users.

Table 5 demonstrates that both participants with and without previous experience with AR/VR headsets had similar levels of satisfaction, which were around 7 and a few around 8. However, when it comes to learning, participants without previous experience had significantly lower satisfaction than those with previous experience, with an average score of 6.8. This indicates that participants without previous experience faced difficulties in using the system compared to those with previous experience. Levene's test analysis indicated that two of the measured constructs, learning and overall impressions, scored values less than 0.05 with values of 0.02 and 0.01, respectively. This confirms the correlation between previous experience and the satisfaction of the learning experience in the system. Moreover, the overall impressions of using the system correlated with the previous experience of similar headsets. This indicates that the more use of these technologies, the more tendency there is to enrich the user experience, learn more functions, and admire them. However, the other three constructs, including holograms, terminology and system information, and system capabilities, had *p* values greater than 0.05, suggesting that the variances were homogeneous and the differences were insignificant.

The next step involves conducting a *T*-test analysis of the constructs. The significance of the construct is determined using a two-tailed approach. The *p* value for holograms is 0.002; for terminology and system information, it is 0.11; for learning, it is < 0.001; for system capabilities, it is 0.06, and for overall reactions to the system, it is 0.07. Except for learning and holograms, the *p* values for the remaining three constructs are greater than 0.05, which means they are not significant, and hence the null hypothesis is not rejected. This implies that there is no significant difference in these three constructs. However, the *p* values for learning and holograms are less than 0.05, which is statistically significant. This indicates that the null hypothesis is rejected, suggesting a significant difference in the experience of using AR and VR headsets.

5.3 UEQ results

Forty-four participants assessed tangible elements of user experience using the UEQ, which is a questionnaire consisting of 26 items with a Likert 7-point scale. The 26 items are categorised into six scales, namely attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty—as demonstrated in Fig. 14. The scales can be classified into two groups: pragmatic quality (which includes perspicuity, efficiency, and dependability) and hedonic quality (which includes stimulation and novelty). Pragmatic quality pertains to task-related quality aspects, while hedonic quality pertains to non-task-related quality aspects.

The analysis of reliability in Table 6 suggests that the UEQ used in the study has a satisfactory level of consistency. This can be inferred from Table 6, which shows that Cronbach's alpha value for the UEQ is higher than 0.7. The study's six constructs, including attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty, demonstrate a certain level of reliability and consistency, indicating that the UEQ's credibility is quite high. Table 6 also demonstrates the 5% confidence intervals per scale, as it is used to measure the accuracy of the estimated scale mean and determine the high scores for relevant UX scales. The confidence interval reflects the level of precision of the estimation, and a smaller confidence interval suggests greater accuracy and reliability of the results.

The UEQ utilised the Likert 7-point scale that covers a range from -3 (indicating very poor) to $+3$ (meaning outstanding). Among the six categories listed in Table 6, each one had an average score of over 1.1. Among the categories, attractiveness had the highest level of variation in the data, while dependability had the lowest. The sequence of data dispersion, from highest to lowest, was attractiveness,

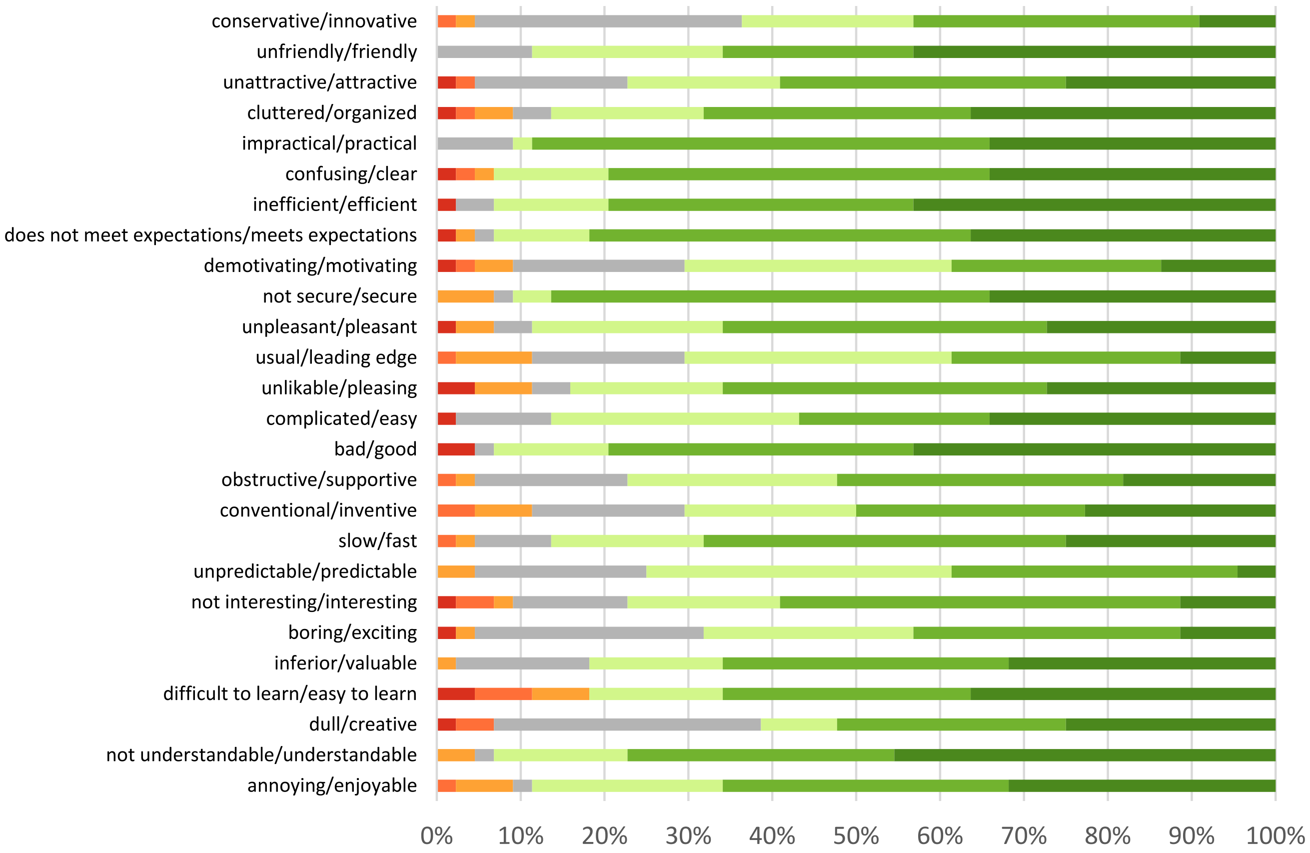


Fig. 14 UEQ responses per item (n = 44), dark red (− 3), light red (− 2), Gray (0), light green (1), green (2), dark green (3)

Table 6 Statistical analysis and reliability for UEQ scale

Confidence intervals ($p = 0.05$) per scale							
Scale	Mean	Std. Dev	*N*	Confidence	Confidence interval		Cronbach's alpha
Attractiveness	1.754	1.145	44	0.338	1.415	2.092	0.85
Perspicuity	1.813	1.116	44	0.330	1.483	2.142	0.79
Efficiency	1.926	0.893	44	0.264	1.662	2.190	0.75
Dependability	1.653	0.836	44	0.247	1.406	1.900	0.75
Stimulation	1.318	1.065	44	0.315	1.003	1.633	0.86
Novelty	1.165	0.978	44	0.289	0.876	1.454	0.72

perspicuity, stimulation, novelty, efficiency, and dependability. Regarding the mean values for the six constructs, it found that the aspect of the MR training system with the highest average rating (1.926) is Efficiency. This indicates that users can easily gain the desired skills and perform the practical tasks of investigation via the system. On the other hand, the dimension with the lowest mean score is novelty (1.165), which is still in the expected UX standard. The mean value of novelty suggests further enhancements are required to make the training system more appealing and provide users with a new experience.

As demonstrated in Fig. 13, the six UEQ constructs' scales are in the range of positive evaluation except for the novelty, which is slightly pass the standards of the user experience values. Overall, the MR training system has a positive user experience, with impressions of attractiveness, perspicuity, efficiency, dependability, and stimulation.

The UEQ framework consists of three components: attractiveness, pragmatic quality, and hedonic quality. The analysis of the gathered data can be categorised into these three groups, as shown in Fig. 15. The pragmatic quality component pertains to the technical focus of product,

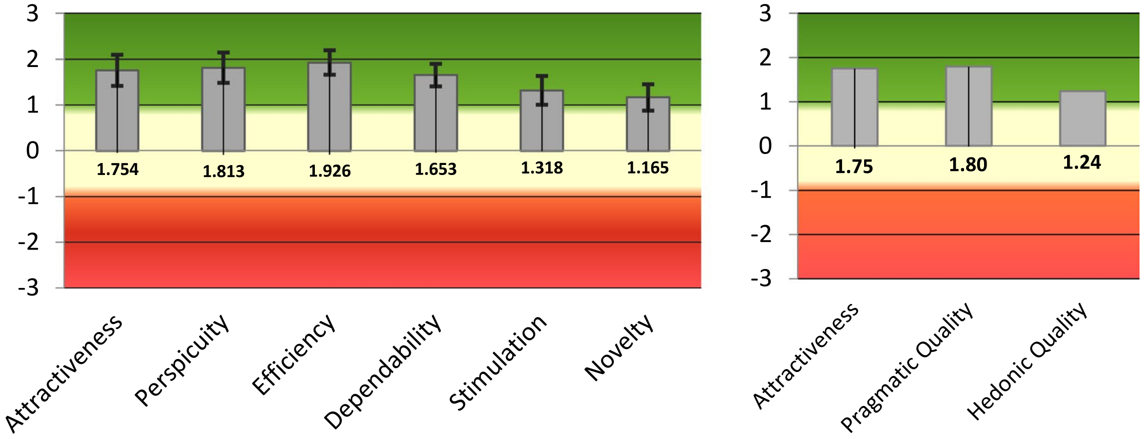


Fig. 15 (Left) UEQ constructs' scale results, (Right) Attractiveness, pragmatic and hedonic quality results

system or service design in achieving goals. It can be attained by ensuring quick and efficient completion of tasks (efficiency), clear understanding (perspicuity), and reliability (dependability). The hedonistic quality component, on the other hand, is concerned with non-technical aspects that relate to user emotions (Schrepp et al. 2014b). The results of this classification are displayed on the right side of Fig. 16, with pragmatic having the highest average value (1.80), while the hedonic quality group has the lowest average value (1.24).

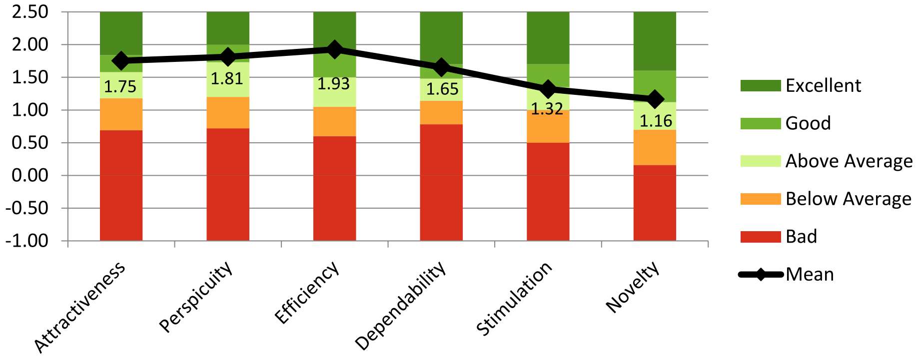
In order to determine if MR training system is considered satisfactory, it is necessary to compare its UEQ value with the benchmark data provided in (Schrepp et al. 2014b). The benchmark data is categorised into five groups: excellent, good, above average, below average, and bad. The excellent category refers to systems that rank within the top 10% of results, while the bad category includes systems that rank within the worst 25% of results. To determine the category of the MR training system, its results are compared to the benchmark data, as depicted in Fig. 15. Each element in MR training system has a different mean value, and the efficiency element section will be rated as good if it has a mean value greater than 1.10, while the novelty element section will be rated as above average if it has a mean value greater than 0.80.

The results of the UEQ score represent the mean value for each element obtained from the questionnaire calculation using UEQ, marking the results for each element. The MR training system performs well in all elements of UX, with the highest achievable categories being Efficiency, Perspicuity, Attractiveness, Dependability, Stimulation and Novelty. The mean efficiency score is 1.93, Perspicuity is 1.81, Attractiveness is 1.75, Dependability is 1.65, Stimulation is 1.32, and Novelty is 1.16. This indicates that the MR training system is a user-friendly software that is easy to learn, efficient, and clear.

6 Discussion

The results presented in the study show the demographic breakdown of the participants and their level of experience and familiarity with XR technologies, specifically MR, using Microsoft HoloLens 2.0. The study aimed to evaluate the user experience and user interaction of an MR system designed to simulate real-life crime scenes and

Fig. 16 UEQ Benchmark for the MR training system



enhance the investigation skills of young police officers. The participants in the study were 44 trained investigators from the Police Academy in Kuwait, all of whom were over 18 years old. The gender distribution of the participants was slightly imbalanced, with 56.8% being male and 43.1% being female.

The study also examined the participants' familiarity with XR technologies. The majority of the participants (70.45%) had generic knowledge of XR technologies, indicating that they were aware of the concept and its applications. Moreover, 59% of the participants had actually used AR/VR applications or solutions, while 40.9% had not been exposed to such experiences. The researcher enquired about the reason for this unique experience in the police academy during the experimentation, and it was concluded that they had a series of events, seminars and workshops to acknowledge them about AR/VR technologies. One notable finding from the study was that a high percentage of students (75%) expressed willingness to use the MR system if it could support the entire practical program, even though the system used in the study was a demo and did not include the comprehensive part of the investigation training. This suggests that the participants recognised the potential value of MR technology in enhancing their investigation skills and were open to incorporating it into their training program.

Regarding the QUIS questionnaires, the reliability analysis showed a satisfactory level of consistency and reliability, as indicated by Cronbach's alpha score exceeding 0.7, according to Nunnally and Bernstein 3rd (1994). The participants expressed a high level of satisfaction with the system across the five constructs of the questionnaire. In terms of the constructs, the "holograms" construct received the highest satisfaction score, suggesting that participants had a positive experience with the visual components of the system. The mean values for the constructs ranged from 7.41 to 7.93, with the overall impression construct receiving the highest score and the learning construct receiving the lowest score. When evaluating the specific aspects presented in the questionnaire, most participants reported high satisfaction ratings. Particularly, participants found the system fun to use and expressed the belief that it would be useful in crime investigation training. They also indicated that the system maintained their interest and that they were satisfied with the user interface aspects, such as differentiating button colours. Additionally, participants expressed a willingness to see more practical training modules and indicated a willingness for future use of the system.

However, there were two aspects in which participants encountered difficulty or expressed lower levels of satisfaction. These aspects were related to "Instructions for hand interactions" in the "Terminology and System Information" construct and "Time to learn to use the system" in the "learning" construct. It seems that participants faced challenges or felt less satisfied with these specific elements of the system.

Levene's test was conducted to assess the significance of the differences among the constructs. The *p*-values for holograms, terminology and system information, learning, and system capabilities were greater than 0.05, indicating no significant differences among them and suggesting homogeneity of variance. However, the *p*-value for overall impressions was 0.04, which is considered significant since it is less than 0.05. This indicates that there is a significant correlation between female participants' usage of the system and their positive overall impressions. This indicates that female users had a more positive perception of the system overall compared to male users. These findings provide insights into the potential impact of gender on user experience. They can inform future developments and adaptations of the MR system to cater to the specific needs and preferences of different user groups. Moreover, some published studies reported higher satisfaction levels and acceptance of software and information systems generically compared to male users (Hargittai 2007; Venkatesh et al. 2003; Beldad et al. 2010; Zhou et al. 2014). One possible explanation for this difference could be related to the way individuals engage with technology. Previous research has shown that there can be gender disparities in technology acceptance and usage patterns (Oyibo and Vassileva 2017). Females may exhibit different preferences for user interfaces, interaction styles, or visual aesthetics, which could influence their overall impressions of the MR system. It would be valuable to explore these factors in more detail to gain a deeper understanding of the underlying reasons for the observed gender difference.

It was also found that the learning and overall impressions constructs significantly correlate with previous experience with similar headsets and satisfaction in these aspects. This suggests that participants with prior experience were more comfortable with the system's learning process and had a more positive overall impression of using the system. The results imply that familiarity with AR/VR technologies enhances the learning experience and contributes to a more positive perception of the system overall.

The results related to the UEQ indicate that the participants assessed tangible elements of user experience using a questionnaire consisting of 26 items, categorized into six scales: attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. The reliability analysis of the UEQ demonstrated a satisfactory level of consistency, as indicated by Cronbach's alpha value exceeding 0.7. This suggests that the questionnaire used in the study has a high level of credibility and reliability. The six constructs of the UEQ, representing different aspects of user experience, showed a certain level of reliability and consistency.

Among the six categories, each had an average score of over 1.1. The data dispersion, from highest to lowest, was observed in the following order: attractiveness, perspicuity, stimulation, novelty, efficiency, and dependability. In terms of the mean values for the six constructs, the aspect of efficiency received the highest average rating (1.926), suggesting that users found it easy to gain the desired skills and perform practical tasks of investigation through the MR training system. On the other hand, the novelty had the lowest mean score (1.165), indicating that further enhancements are required to make the training system more appealing and provide users with a new and engaging experience. The results from the UEQ provide insights into various dimensions of user experience. While the system was found to be efficient and practical, there is room for improvement in terms of novelty to enhance the overall user experience. These findings can guide future iterations and refinements of the MR training system, aiming to create a more attractive and engaging experience for users.

Thus, the study suggests that the MR system using Microsoft HoloLens 2.0 provided a valuable training experience for young police officers, with high levels of satisfaction reported in various aspects. The results support the use of MR technology as a cost-effective and practical solution for simulating real-life crime scenes in forensic science education. The feedback from participants can inform further improvements and refinements to enhance user experience and address the identified challenges.

Building a MR training system as an alternative to using actual crime scenes for training young investigators can have several significant advantages:

- Minimizing crime scene contamination: Crime scenes are delicate environments where evidence can easily be contaminated or destroyed. By utilising a MR training system, young investigators can learn and practice their skills without the risk of causing unintentional contamination. This ensures that real crime scenes remain pristine and valuable evidence is preserved for accurate analysis.
- Cost-effectiveness: Conducting training sessions in real crime scenes can be expensive due to various factors such as location, security arrangements, and cleanup requirements. By using a MR training system, the cost of training can be significantly reduced. Virtual environments can be created at a fraction of the cost, making them more accessible and scalable for training a larger number of investigators.
- Immersive and realistic simulations: MR training systems can provide an immersive and realistic experience for young investigators. By recreating crime scenes virtually, trainees can practice their investigation techniques in a simulated environment that closely resembles real-life scenarios. They can interact with virtual evidence, examine crime scenes from different angles, and perform forensic procedures, enhancing their skills and familiarity with investigative procedures.
- Controlled learning environment: In a MR training system, instructors have complete control over the training environment. They can tailor scenarios, introduce specific challenges, and provide immediate feedback to trainees. This controlled learning environment allows investigators to practice and refine their skills in a safe and supportive setting, ensuring that they are well-prepared before handling actual crime scenes.
- Repetition and skill development: Training in a MR system offers the advantage of repetition and skill development. Trainees can repeat specific scenarios multiple times, focusing on different aspects of the investigation and improving their techniques. This iterative learning process allows investigators to refine their observation skills, evidence-collection methods, and critical thinking abilities, ultimately enhancing their investigative capabilities.
- Flexibility and adaptability: MR training systems provide flexibility and adaptability in training. Various types of crime scenes and scenarios can be simulated, covering a wide range of investigative challenges and techniques. Investigators can be exposed to different crime scenarios, including rare or complex cases, preparing them to handle diverse situations they might encounter in their careers.
- Collaboration and remote training: In future versions of MR training systems, there is a potential to facilitate collaborative learning and remote training opportunities. Investigators can work together in virtual crime scenes, sharing information and collaborating on solving cases. Additionally, remote training becomes feasible, allowing investigators from different locations to train simultaneously, share experiences, and learn from each other's insights.

It is essential to acknowledge the foundational role played by ELT in designing the system adopting the participatory design approach. The MR system was specifically designed to facilitate each of the four stages of ELT—CE, RO, AC, and AE—to ensure a holistic and effective learning experience. For the Concrete Experience, the MR environment provided trainees with immersive simulations of crime scenes, offering firsthand sensory interactions akin to real-world experiences. This stage was crucial in establishing a baseline of practical skills and situational awareness. In regards to RO: Following the immersive experiences, the system guided trainees through a reflective process where they could review and assess their actions within the simulations. This reflection helped to highlight areas of strength and opportunities for improvement, fostering a deeper understanding of their own investigative processes. For the

AC, The MR system supported the transition from practical engagement to theoretical analysis, allowing trainees to contextualise their hands-on experiences within broader forensic principles. This stage bridged the gap between doing and understanding, providing trainees with a framework to rationalise and verbalise their experiences. In regards to AE, the MR technology enabled trainees to apply their newly acquired knowledge and insights in new, varied scenarios within the simulated environment. This stage was essential for reinforcing learning through repeated practice and experimentation, allowing trainees to explore different approaches and solutions in a controlled, risk-free setting.

One limitation of a MR training system for young investigators is the potential lack of complete realism compared to real-life crime scenes. While virtual and reconstructed environments can closely simulate crime scenes, there may still be certain subtle nuances, complexities, and unpredictable factors that are difficult to replicate accurately in a virtual setting. Real crime scenes are dynamic and often present unexpected challenges, such as varying lighting conditions, weather effects, or the presence of external influences that may affect the evidence. These factors can be challenging to recreate faithfully in an MR training system. As a result, investigators may not fully experience the same level of pressure, urgency, and adaptability required when working at an actual crime scene. Moreover, it is crucial to highlight the nuanced understanding of the deviations associated with 3D scanning technologies, particularly when employing devices such as the FARO X 130 scanner. As delineated in the analysis presented, while the potential for minor deviations in the scanning process exists, their impact is significantly mitigated when applied to small indoor venues.The inherent characteristics of the FARO X 130, with its declared distance error of approximately ± 2 mm at a distance of 40 m and a high scanning density yielding a surface area of about 6×6 mm per scan point, showcase the device's adeptness in capturing detailed spatial data within confined spaces. This level of precision is particularly advantageous in indoor environments, where the proximity of objects and the reduced scope of the scanning area enhance the scanner's efficacy in producing accurate and reliable representations. Furthermore, one of the most influential factors to alter measurements is the laser beam's diameter, particularly in open space, however, its divergence extremely reduced within indoor settings, as suggested by Wieczorek et al. (2019). Given the shorter distances involved in such environments, these elements, which could potentially introduce deviations in larger, open-area scans, have a diminished impact, thereby contributing to the integrity of the scan data. It is also pertinent to address the role of operator expertise and the precision of point indication in the scanning process. In the controlled conditions of an indoor venue, the potential for operator-induced errors is lessened, thanks to the more manageable environment and the clearer visibility of characteristic points. This controlled setting allows for a more accurate selection of measuring points, reducing ambiguities and enhancing the overall reliability of the scanned data.

Another limitation concerned the artificial clues detected in the scanned scenes. Therefore, in light of these considerations, it is crucial for users, particularly those who are in the early stages of their investigative careers, to be aware of these limitations and the potential impact they may have on the analysis and interpretation of virtual crime scenes. It is important for users to develop a critical understanding of the technology's capabilities and to approach the analysis of virtual crime scenes with an awareness of the potential for inaccuracies and distortions. We aim to enhance the post-processing stage by eliminating these artifacts to provide a more credible and realistic scene that reflects the authenticity of an actual crime scene. Furthermore, the tactile and sensory aspects of working with physical evidence may be limited in a virtual environment. Investigators rely on their senses, such as touch, smell, and even intuition, to gather information and make critical observations. Although MR can provide visual and auditory stimuli, it may not fully replicate the tactile feedback and overall sensory experience that investigators encounter in real-life investigations. To mitigate this limitation, supplementary training components such as hands-on workshops, field exercises, and internships at real crime scenes should be incorporated into the overall training program. These practical experiences would help bridge the gap between the simulated virtual environment and the complexities of real crime scenes, allowing investigators to develop a well-rounded skill set.

7 Conclusion and future research

The research presented a novel process of designing and developing of an MR system for crime scene investigation training. The authors argue that such a system can provide a cost-effective and efficient alternative to traditional training methods due to the currently limited accessibility of real crime scenes for young investigators to practice. The study is particularly significant since crime scene investigation is a complex and high-stakes process requiring great skill and attention to detail.

The paper employs system questionnaires for QUIS and UEQ to evaluate the system's user interaction and user experience. The QUIS questionnaire was designed to assess user satisfaction with the system's usability, while the UEQ questionnaire was employed to evaluate the user experience in terms of attractiveness, efficiency, effectiveness, and satisfaction.

The results of the study showed that the MR system was effective in providing a realistic and immersive crime scene investigation experience. The QUIS questionnaire revealed that the system was easy to use and showed positive satisfaction for the user experience considering the constructs: holograms, terminology, system information learning, system capabilities, and overall impressions. At the same time, the UEQ questionnaire showed that the system has excellent efficiency, good perspicuity, dependability, simulation, attractiveness and novelty. Consequently, the MR training system is able to meet user expectations in terms of attractiveness and pragmatic quality.

Building a MR training system for trained investigators offers numerous benefits, including minimising crime scene contamination, cost-effectiveness, enhancing investigation skills, providing immersive simulations, offering controlled learning environments, enabling skill development, ensuring flexibility and adaptability, and facilitating collaboration and remote training. Such a system can revolutionise investigative training, preparing investigators to handle real-world crime scenes effectively while preserving the integrity of actual crime scenes.

In the meantime, authors are working on expanding the investigation training system to include remote students to allow the concept of collaborative investigation with the involvement of their trainer to witness the progress of the learning and practices. This will allow the sharing of knowledge between investigators and will open new areas for building new capabilities in the training modules. It will also add more scenarios, including indoor and outdoor scenes, with more complex cases and more different levels of difficulty. Moreover, it was planned to incorporate part of the training to include the best practice prerequisites, such as wearing gloves before entering the scene and methods to avoid contaminating the crime scene. Authors are also willing to incorporate artificial intelligence (AI) into the investigation training modules to help students gain knowledge and reflect on the investigated scenes.

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Declarations

Conflict of interest No potential conflict of interest was reported by the author(s).

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of Liverpool John Moores University and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

References

Adamczyk M, Hołowko E, Lech K, Michoński J, Mączkowski G, Bolewicki P, Januszkiewicz K, Sitnik R (2017) Three-dimensional measurement system for crime scene documentation counterterrorism, crime fighting, forensics, and surveillance technologies. SPIE 10441:88–99

Ahn J, Choi S, Lee M, Kim K (2017) Investigating key user experience factors for virtual reality interactions. J Ergono Soc Korea 36:267–280

Alshawabkeh Y, Baik A, Miky Y (2021) Integration of laser scanner and photogrammetry for heritage BIM enhancement. ISPRS Int J Geo Inf 10:316

Altarteer S, Charissis V, Harrison D, Chan W (2013) Interactive virtual reality shopping and the impact in luxury brands. In: International conference on virtual, augmented and mixed reality, Springer, pp 221–230

Arifin Y, Sastria TG, Barlian E (2018) User experience metric for augmented reality application: a review. Procedia Comput Sci 135:648–656

Arrighi G, See ZS, Jones D (2021) Victoria theatre virtual reality: a digital heritage case study and user experience design. Digit Appl Archaeol Cult Herit 21:e00176

Bayarri S, Fernandez M, Perez M (1996) Virtual reality for driving simulation. Commun ACM 39:72–76

Beebe NL, Clark JG (2005) A hierarchical, objectives-based framework for the digital investigations process. Digit Investig 2:147–167

Beldad A, de Jong M, Steehouder M (2010) How shall I trust the faceless and the intangible? A literature review on the antecedents of online trust. Comput Hum Behav 26:857–869

Bermejo C, Hui P (2021) A survey on haptic technologies for mobile augmented reality. ACM Computing Surv (CSUR) 54:1–35

Bolliger MJ, Buck U, Thali MJ, Bolliger SA (2012) Reconstruction and 3D visualisation based on objective real 3D based documentation. Forensic Sci Med Pathol 8:208–217

Buck U, Naether S, Räss B, Jackowski C, Thali MJ (2013) Accident or homicide–virtual crime scene reconstruction using 3D methods. Forensic Sci Int 225:75–84

Bulgakov V, Trushchenkov I, Bulgakova E (2019) Spherical panoramic photo shooting and virtual reality demonstration of a crime scene. In: Conference on creativity in intelligent technologies and data science, Springer, pp 217–225

Cadet LB, Chainay H (2020) Memory of virtual experiences: role of immersion, emotion and sense of presence. Int J Hum Comput Stud 144:102506

Cai Z-F, Liu D-J, Zhang A-Y (2002) Scheme study of automobile driving training simulator based on virtual reality Xi Tong Fang Zhen Xue Bao: Zhongguo Xi Tong Fang Zhen Xue Hui Hui Kan= J Syst Simul 14(6):771–774

Carmel D, Dayan E, Naveh A, Raveh O, Ben-Shakhar G (2003) Estimating the validity of the guilty knowledge test from simulated experiments: the external validity of mock crime studies. J Exp Psychol Appl 9:261–269

Chan JC, Leung H, Tang JK, Komura T (2010) A virtual reality dance training system using motion capture technology. IEEE Trans Learn Technol 4:187–195

Chin J, Diehl V, Norman K (1988a) Questionnaire for user interaction satisfaction (QUIS). In: Human-computer interaction lab, University of Maryland at College Park

Chin JP, Diehl VA, Norman KL (1988b) Development of an instrument measuring user satisfaction of the human-computer interface. In: Proceedings of the SIGCHI conference on Human factors in computing systems, pp 213–218

Cho J, Jung T, Macleod K, Swenson A (2021) Using virtual reality as a form of simulation in the context of legal education. Springer, Augmented Reality and Virtual Reality

Colard T, Delannoy Y, Bresson F, Marechal C, Raul J-S, Hedouin V (2013) 3D-MSCT imaging of bullet trajectory in 3D crime scene reconstruction: two case reports. Leg Med 15:318–322

Cumbo B, Selwyn N (2022) Using participatory design approaches in educational research. Int J Res Method Educ 45:60–72

Datcu D, Lukosch SG, Lukosch HK (2016) A collaborative game to study presence and situational awareness in a physical and an augmented reality environment. J Univers Comput Sci 22:247–270

Dostal C, Yamafune K (2018) Photogrammetric texture mapping: a method for increasing the Fidelity of 3D models of cultural heritage materials. J Archaeol Sci Rep 18:430–436

Duea SR, Zimmerman EB, Vaughn LM, Dias S, Harris J (2022) A guide to selecting participatory research methods based on project and partnership goals. J Particip Res Method 3(1):1–28

Ebert LC, Nguyen TT, Breitbeck R, Braun M, Thali MJ, Ross S (2014) The forensic holodeck: an immersive display for forensic crime scene reconstructions. Springer

Elhaw AE, Alshehhi DJ (2024) Using virtual reality in (investigating-simulating-reconstructing) the crime scene. Int J Intell Syst Appl Eng 12:530–555

Engelbrecht H, Lukosch SG (2018) Viability of augmented content for field policing. In: 2018 IEEE international symposium on mixed and augmented reality adjunct (ISMAR-Adjunct), IEEE, pp 386–389

Fang T-Y, Wang P-C, Liu C-H, Su M-C, Yeh S-C (2014) Evaluation of a haptics-based virtual reality temporal bone simulator for anatomy and surgery training. Comput Method Progr Biomed 113:674–681

Faro (2021) Checkerboard registration targets download for the laser scanner or hand-held scanner [Online]. FARO. Available: https://knowledge.faro.com/Hardware/3D_Scanners/Focus/Checkerboard_Registration_Targets_Download_for_the_Laser_Scanner_or_Hand-Held_Scanner [Accessed 24th May 2022]

Filigenzi MT, Orr TJ, Ruff TM (2000) Virtual reality for mine safety training. Appl Occup Environ Hyg 15:465–469

Fisher BA (2012) Ethics in the crime laboratory and in crime scene investigations. Academic Press, Oxford

Flight C, Ballantyne KN (2022) Determining the accuracy of the ‘place in 3D’ function in FARO Scene. J Assoc Crime Scene Reconstr 26

Galanakis G, Zabulis X, Evdaimon T, Fikenscher S-E, Allertseder S, Tsikrika T, Vrochidis S (2021) A study of 3D digitisation modalities for crime scene investigation. Forensic Sci 1:56–85

Gatto C, Liaci S, Corchia L, Chiarello S, Faggiano F, Sumerano G, DE, Paolis LT (2022) Extended reality technologies and social inclusion: the role of virtual reality in includiamoci project. In: Extended reality: first international conference, XR salento 2022, Lecce, Italy, July 6–8, 2022, Proceedings, Part I, 2022. Springer, pp 335–346

Gee AP, Escamilla-Ambrosio PJ, Webb M, Mayol-Cuevas W, Calway A (2010) Augmented crime scenes: virtual annotation of physical environments for forensic investigation. In: Proceedings of the 2nd ACM workshop on multimedia in forensics, security and intelligence, pp 105–110

Ghazwani Y, Smith S (2020) Interaction in augmented reality: Challenges to enhance user experience. In: Proceedings of the 2020 4th international conference on virtual and augmented reality simulations, pp 39–44

Gregory J (2003) Scandinavian approaches to participatory design. Int J Eng Educ 19:62–74

Ha T, Woo, W, Lee Y, Lee J, Ryu J, Choi H, Lee, K (2010) ARtalet: tangible user interface based immersive augmented reality authoring tool for Digilog book. In: 2010 International symposium on ubiquitous virtual reality, IEEE, pp 40–43

Haque SEI, Saleem S (2020) Augmented reality based criminal investigation system (arcrime). In: 2020 8th International symposium on digital forensics and security (ISDFS), IEEE, pp 1–6

Hargittai E (2007) Whose space? Differences among users and non-users of social network sites. J Comput-Mediat Commun 13:276–297

Hassenzahl M, Tractinsky N (2006) User experience-a research agenda. Behav Inf Technol 25:91–97

Hinderks A, Schrepp M, Mayo FJD, Escalona MJ, Thomaschewski J (2019) Developing a UX KPI based on the user experience questionnaire. Comput Stand Interfac 65:38–44

Hornbæk K (2006) Current practice in measuring usability: challenges to usability studies and research. Int J Hum Comput Stud 64:79–102

Huang CL, Luo YF, Yang SC, Lu CM, Chen A-S (2020) Influence of students’ learning style, sense of presence, and cognitive load on learning outcomes in an immersive virtual reality learning environment. J Educ Comput Res 58:596–615

Huber T, Paschold M, Lang H, Kneist W (2015) Influence of a camera navigation training on team performance in virtual reality laparoscopy. J Surg Simul 2:35–39

ISO (2019) Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems. ISO.org., ISO pp 9241–210

Jacobs C (2004) *Interactive panoramas: techniques for digital panoramic photography*, Springer Science & Business Media

Jani G, Johnson A (2022) Virtual reality and its transformation in forensic education and research practices. J vis Commun Med 45:18–25

Johnson RR (1998) User-centered technology: A rhetorical theory for computers and other mundane artifacts, SUNY press

Kader SN, Ng WB, Tan SWL, Fung FM (2020) Building an interactive immersive virtual reality crime scene for future chemists to learn forensic science chemistry. J Chem Educ 97:2651–2656

Karabiyik U, Mousas C, Sirota D, Iwai T, Akdere M (2019) A virtual reality framework for training incident first responders and digital forensic investigators. In: International symposium on visual computing, Springer, pp 469–480

Kilgus T, Heim E, Haase S, Prüfer S, Müller M, Seitel A, Fangerau M, Wiebe T, Iszatt J, Schlemmer H-P (2015) Mobile markerless augmented reality and its application in forensic medicine. Int J Comput Assist Radiol Surg 10:573–586

Kim J, Luu W, Palmisano S (2020) Multisensory integration and the experience of scene instability, presence and cybersickness in virtual environments. Comput Hum Behav 113:106484

Kim J, Leathem T (2018) Virtual reality as a standard in the construction management curriculum. In: International conference on construction futures, pp 1–13

Kline D, Wang M, Tieto, V, WEN Q (2022) Spatial awareness getting started — MRTK2 [Online]. Microsoft. Available: https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/features/spatial-awareness/spatial-awareness-getting-started?view=mrtkunity-2022-05 [Accessed 12th September 2022].

Kolb AY (2005) The Kolb learning style inventory-version 3.1 2005 technical specifications. Boston MA Hay Resour Dir 200:166–171

Kolb D, Tile T, Puei TH, Hall P, Jords K (1984). Experiential learning: experience as the source of learning and development

Kopeć W, Wichrowski M, Kalinowski K, Jaskulska A, Skorupska K, Cnotkowski D, Tyszka J, Popieluch A, Voitenkova A, Masłyk R (2019) VR with older adults: participatory design of a virtual ATM training simulation. IFAC-PapersOnLine 52:277–281

Kottner S, Ebert LC, Ampanozi G, Braun M, Thali MJ, Gascho D (2017) VirtoScan-a mobile, low-cost photogrammetry setup for fast post-mortem 3D full-body documentations in x-ray computed tomography and autopsy suites. Forensic Sci Med Pathol 13:34–43

Kowalski P, Skabek K (2018) The accuracy of a scene geometry based on the terrestrial laser scanner measurements. In: Man-machine interactions 5: 5th international conference on man-machine interactions, ICMMI 2017 Held at Kraków, Poland, October 3–6, 2017. Springer International Publishing, pp 408–417

Ktena SI, Abbott W, Faisal AA (2015) A virtual reality platform for safe evaluation and training of natural gaze-based wheelchair driving. In: 2015 7th International IEEE/EMBS conference on neural engineering (NER), IEEE, pp 236–239

Kyan M, Sun G, Li H, Zhong L, Muneesawang P, Dong N, Elder B, Guan L (2015) An approach to ballet dance training through ms kinect and visualization in a cave virtual reality environment. ACM Trans Intell Syst Technol (TIST) 6:1–37

Laugwitz B, Held T, Schrepp M (2008) Construction and evaluation of a user experience questionnaire. In: Symposium of the Austrian HCI and usability engineering group. Springer, pp 63–76

Lee J-H, Lee C-F (2019) Extension of TAM by perceived interactivity to understand usage behaviors on ACG social media sites. Sustainability 11:5723

Lee H-G, Chung S, Lee W-H (2013a) Presence in virtual golf simulators: the effects of presence on perceived enjoyment, perceived value, and behavioral intention. New Media Soc 15:930–946

Lee Y-C N, Shan L-T, Chen C-H (2013b) System development of immersive technology theatre in museum. In: International conference on virtual, augmented and mixed reality, Springer, pp 400–408

Leung WS, Blauw FF (2020) An augmented reality approach to delivering a connected digital forensics training experience. Springer, Information Science and Applications

Levstein I, Justice LJ (2019) Csi4fs®: A markerless augmented reality game–a novel approach to crime scene investigation training. Emerging technologies in virtual learning environments, IGI Global

Liang H, Li W, Lai S, Zhu L, Jiang W, Zhang Q (2018) The integration of terrestrial laser scanning and terrestrial and unmanned aerial vehicle digital photogrammetry for the documentation of Chinese classical gardens–A case study of Huanxiu Shanzhuang, Suzhou, China. J Cult Herit 33:222–230

Lindgren R, Tscholl M, Wang S, Johnson E (2016) Enhancing learning and engagement through embodied interaction within a mixed reality simulation. Comput Educ 95:174–187

Lindsay PH, Norman DA (2013) Human information processing: An introduction to psychology, Academic press

Lukosch H, Van Ruijven T, Verbraeck A (2012) The participatory design of a simulation training game. In: Proceedings of the 2012 winter simulation conference (WSC), IEEE, pp 1–11

Lynnerup N, Clausen M-L, Kristoffersen AM, Steglich-Arnholm H (2009) Facial recognition and laser surface scan: a pilot study. Forensic Sci Med Pathol 5:167–173

Ma M, Zheng H, Lallie H (2010) Virtual reality and 3D animation in forensic visualization: 3D animation in forensic visualization. J Forensic Sci 55:1227–1231

Mach V, Valouch J, Adámek M, Ševčík J (2019) Virtual reality–level of immersion within the crime investigation. In: MATEC web of conferences, EDP Sciences, 01031

Martín-Gutiérrez J, Fabiani P, Benesova W, Meneses MD, Mora CE (2015) Augmented reality to promote collaborative and autonomous learning in higher education. Comput Hum Behav 51:752–761

Maulana FI, Wijaya IBA, Azis B, Harjo AA, Suwondo, L, Livianty V (2022) Evaluation of user experience on the augmented reality glovic cafe and bakery jember application to maximize user experience. In: 2022 8th International conference on education and technology (ICET), IEEE, pp 270–274

Mayne R, Green H (2020) Virtual reality for teaching and learning in crime scene investigation. Sci Justice 60:466–472

Mennell J (2006) The future of forensic and crime scene science: part II. A UK perspective on forensic science education. Forensic Sci Int 157:S13–S20

Mentzelopoulos M, Parrish J, Kathrani P, Economou D. (2016) REVRLAW: An immersive way for teaching criminal law using virtual reality. International conference on immersive learning, Springer, pp 73–84

Meshal A, Hoshang K, Ramy H, Tanzila S (2023) Seamless crime scene reconstruction in mixed reality for investigation training: a design and evaluation study. IEEE Transactions on Learning Technologies

Morélot S, Garrigou A, Dedieu J, N'Kaoua B (2021) Virtual reality for fire safety training: influence of immersion and sense of presence on conceptual and procedural acquisition. Comput Educ 166:104145

Muller MJ, Kuhn S (1993) Participatory design. Commun ACM 36:24–28

Noghabaei M, Asadi K, Han K (2019) Virtual manipulation in an immersive virtual environment: simulation of virtual assembly. In: Computing in civil engineering, 2019 visualization, information modeling, and simulation american society of civil engineers Reston VA

Norman K, Shneiderman B (1989). Questionnaire for user interaction satisfaction (QUIS 5.0). HCI Lab, College Park, University of Maryland

Nunnally J, Bernstein I (1994) Psychometric theory, 3rd edn. McGrawHill, New York

Oyibo K, Vassileva J (2017) The interplay of aesthetics, usability and credibility in mobile website design and the effect of gender. J Interact Syst 8:174–188

Papachristos NM, Vrellis I, Mikropoulos TAA (2017) comparison between oculus rift and a low-cost smartphone VR headset: immersive user experience and learning. In: 2017 IEEE 17th International conference on advanced learning technologies (ICALT), IEEE, pp 477–481

Paramitha AII, Dantes, GR, Indrawan G (2018) The evaluation of web based academic progress information system using heuristic evaluation and user experience questionnaire (UEQ). In: 2018 Third international conference on informatics and computing (ICIC), IEEE, pp 1–6

Peterson J, Sommers I, Baskin D, Johnson D (2010) The role and impact of forensic evidence in the criminal justice process. National Institute of Justice, pp 1–151

Plantin J (2021) Recovery and prediction of hand motor function after stroke: a longitudinal study using novel methods to quantify hand function and connectivity in brain networks. Karolinska Institutet (Sweden)

Poelman R, Akman O, Lukosch S, Jonker P (2012) As if being there: Mediated reality for crime scene investigation. In: Proceedings of the ACM 2012 conference on computer supported cooperative work pages. Washington, USA

Individual Individual

Ratticò FG, Calandra D, Piviotti M, Lamberti F 2021 Assessing the user experience of consumer haptic devices for simulation-based virtual reality. In: 2021 IEEE 11th international conference on consumer electronics (ICCE-Berlin), IEEE, 1–6

Raneri D (2018) Enhancing forensic investigation through the use of modern three-dimensional (3D) imaging technologies for crime scene reconstruction. Aust J Forensic Sci 50:697–707

Rebenitsch L, Owen C (2016) Review on cybersickness in applications and visual displays. Virtual Reality 20:101–125

Rokhsaritalemi S, Sadeghi-Niaraki A, Choi S-M (2020) A review on mixed reality: current trends, challenges and prospects. Appl Sci 10:636

Roos W (1951) On the definition of fundamental concepts in photogrammetry. Photogrammetria 8:97–110

Rühmann LM, Prilla M, Brown G (2018) Cooperative mixed reality: an analysis tool. In: proceedings of the 2018 ACM conference on supporting groupwork, pp 107–111

Sacks R, Perlman A, Barak R (2013) Construction safety training using immersive virtual reality. Constr Manag Econ 31:1005–1017

Saleh AM, Abuaddous HY, Enaizan O, Ghabban F (2021) User experience assessment of a COVID-19 tracking mobile application (AMAN) in Jordan. Indones J Electr Eng Comput Sci 23:1120–1127

Sandvik K (2010) Crime scenes as augmented reality: Models for enhancing places emotionally by means of narratives, fictions and virtual reality. In: Knudsen BT, Waade AM (eds) Re-investing authenticity: Tourism, place and emotion. Channel View Publications, Bristol, pp 138–153

Šašak J, Gallay M, Kaňuk J, Hofierka J, Minár J (2019) Combined use of terrestrial laser scanning and UAV photogrammetry in mapping alpine terrain. Remote Sens 11:2154

Scholz J, Smith AN (2016) Augmented reality: Designing immersive experiences that maximize consumer engagement. Bus Horiz 59:149–161

Schrepp M (2015) User experience questionnaire handbook. All you need to know to apply the UEQ successfully in your project

Schrepp M, Hinderks A Thomaschewski J 2014a Applying the user experience questionnaire (UEQ) in different evaluation scenarios. In: International conference of design, user experience, and usability, Springer, pp 383–392

Schrepp M, Hinderks A Thomaschewski J (2014b) Applying the user experience questionnaire (UEQ) in different evaluation scenarios. Design, User Experience, and Usability. Theories, Methods, and Tools for Designing the User Experience: In: Third international conference, DUXU 2014, held as Part of HCI international 2014, Heraklion, Crete, Greece, June 22–27, 2014, Proceedings, Part I 3, Springer, 383–392

Servotte J-C, Goosse M, Campbell SH, Dardenne N, Pilote B, Simoneau IL, Guillaume M, Bragard I, Ghuysen A (2020) Virtual reality experience: Immersion, sense of presence, and cybersickness. Clin Simul Nurs 38:35–43

Shamata A, Thompson T (2018) Using structured light three-dimensional surface scanning on living individuals: Key considerations and best practice for forensic medicine. J Forensic Leg Med 55:58–64

Somrak A, Humar I, Hossain MS, Alhamid MF, Hossain MA, Guna J (2019) Estimating VR Sickness and user experience using different HMD technologies: An evaluation study. Futur Gener Comput Syst 94:302–316

Somrak A, Pogačnik M, Guna J (2021) Suitability and comparison of questionnaires assessing virtual reality-induced symptoms and effects and user experience in virtual environments. Sensors 21:1185

Spain R, Goldberg B, Hansberger J, Griffith T, Flynn J, Garneau C, Shorter P, Sinatra A, Key P, Finseth T (2018) Me and my VE, part 5: applications in human factors research and practice. Proc Hum Factors Ergon Soc Annu Meet 62:2051–2055

Speicher M, Hall B D, Nebeling M (2019) What is mixed reality? In: proceedings of the 2019 CHI conference on human factors in computing systems, pp 1–15

Spinuzzi C (2005) The methodology of participatory design. Tech Commun 52:163–174

Spittle B, Frutos-Pascual M, Creed C, Williams I (2022) A review of interaction techniques for immersive environments. IEEE Transactions on Visualization and Computer Graphics,

Steinberg AD, Bashook PG, Drummond J, Ashrafi S, Zefran M (2007) Assessment of Faculty Perception of Content Validity of PerioSim©, a Haptic-3D Virtual Reality Dental Training Simulator. J Dent Educ 71:1574–1582

Streefkerk JW, Houben M, Amerongen PV, Haar FT, Dijk J (2013) The art of csi: an augmented reality tool (art) to annotate crime scenes in forensic investigation. In: International conference on virtual, augmented and mixed reality, Springer, pp 330–339

Studio A (2018) Experience compelling new possibilities for storytelling and gameplay when life-sized characters are aware of your presence, share your real space, and interact with you in mixed reality. [Online]. Asobostudio.com: Microsoft. Available: https://www.asobostudio.com/games/fragments [Accessed 21 September 2022]

Su K-W, Chen S-C, Lin P-H, Hsieh C-I (2020) Evaluating the user interface and experience of VR in the electronic commerce environment: a hybrid approach. Virtual Reality 24:241–254

Suh A, Prophet J (2018) The state of immersive technology research: A literature analysis. Comput Hum Behav 86:77–90

Teo T, Lawrence L, Lee GA, Billinghurst M, Adcock M (2019) Mixed reality remote collaboration combining 360 video and 3d reconstruction. In: Proceedings of the 2019 CHI conference on human factors in computing systems, pp 1–14

Tolstolutsky V, Kuzenkova G, Malichenko V (2021) The experience of using augmented reality in the reconstruction of the crime scene committed in transport. Springer, International Scientific Siberian Transport Forum, pp 1095–1102

Tom Dieck MC, Jung T, Michopoulou E (2019) Experiencing virtual reality in heritage attractions: Perceptions of elderly users. The power of AR and VR for business, Augmented reality and virtual reality, pp 89–98

Tredinnick R, Smith S, Ponto K (2019) A cost-benefit analysis of 3D scanning technology for crime scene investigation. Forensic Sci Int Reports 1:100025

Trushchenkov I, Bulgakov V, Yarmak K, Bulgakova E, Trushchenkova I (2021) Using Virtual Reality Systems for Crime Scene Reconstruction. In: Conference on creativity in intelligent technologies and data science, Springer, pp 325–335 2021

Van Der Velden M, Mörtberg C, 2015 Participatory design and design for values Handbook of ethics, values, and technological design: Sources, theory, values and application domains, pp 41–66

Venkatesh V, Morris MG, Davis GB, Davis FD (2003) User acceptance of information technology: Toward a unified view MIS quarterly, pp 425–478

Vergari M, Kojić T, Vona F, Garzotto F, Möller S, Voigt-Antons J-N (2021) Influence of interactivity and social environments on user experience and social acceptability in virtual reality IEEE Virtual Reality and 3D User Interfaces (VR) IEEE pp 695–704

Villa C, Flies MJ, Jacobsen C (2018) Forensic 3D documentation of bodies: Simple and fast procedure for combining CT scanning with external photogrammetry data. J Forensic Radiol Imag 12:e2–e7

Wang J, Li Z, Hu W, Shao Y, Wang L, Wu R, Ma K, Zou D, Chen Y (2019) Virtual reality and integrated crime scene scanning for immersive and heterogeneous crime scene reconstruction. Forensic Sci Int 303:109943

Wieczorek T, Przyłucki R, Lisok J, Smagór A (2019) Analysis of the accuracy of crime scene mapping using 3D laser scanners. In: Hanus R, Mazur D, Kreischer C (eds) Methods and techniques of signal processing in physical measurements. Springer Nature Switzerland AG, Franklin, MA, US, pp 406–415

Xue H, Sharma P, Wild F (2019) User satisfaction in augmented reality-based training using microsoft HoloLens. Computers 8:9

Yu Y (2017) A mixed reality approach to 3d interactive prototyping for participatory design of ambient intelligence. University of Sheffield 2017

Zhou Z, Jin X-L, Fang Y (2014) Moderating role of gender in the relationships between perceived benefits and satisfaction in social virtual world continuance. Decis Support Syst 65:69–79

Zhu D, Wang D, Huang R, Jing Y, Qiao L, Liu W (2022) User interface (UI) design and user experience questionnaire (UEQ) evaluation of a to-do list mobile application to support day-to-day life of older adults. Healthcare, 2022. MDPI, 2068