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HUMAN PERCEPTION EXPERIMENT IN UNDERGROUND SPACE ENHANCED WITH MIXED REALITY

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Abstract: Underground spaces are rapidly expanding, with their functions increasingly extending to commercial, entertainment, and residential areas. However, the inherent characteristics of closure and complexity in these environments significantly impact user experience and safety. An experimental system was developed to explore human perception in underground spaces.

The system consisted of three main components: a mixed reality (MR) device, a set of wearable biosensors, and a data platform. Typical elements of the underground environment were built by digital tools and overlaid onto real-world physical space using the MR device. Scenarios, such as fire hazards or earthquakes, were simulated based on physical mechanism and introduced into the MR environment. During these simulations, human responses were monitored via wearable biosensors. All data were transmitted to and stored on the data platform, where analysis revealed correlations between human responses and environmental factors, providing insights for the optimization of underground spaces.

A fire drill scenario was studied as the application of this system. Smoke is generated by mixed-reality device according to the data derived from Fire Dynamics Simulator(FDS), after which the participant was asked to find the exit under low visibility. Meanwhile, the response of participants, including electroencephalogram(EEG), electrodermal activity(EDA) and photoplethysmographic(PPG), was collected for further analysis. It was indicated that the system could effectively build a vivid experimental scenario with less modeling work and higher movement freedom than virtual reality(VR) and provided a more immersive experience than augmented reality(AR). The human physiological signal can be recorded and utilized as a supplement for subjective response in the future.

Keywords: human factors, underground space, mixed reality, fire drill

1. INTRODUCTION

Underground spaces are continuously evolving, taking on increasingly diverse functions beyond basic municipal and civil defense purposes. However, certain characteristics of underground environments, such as confined spaces and monotonous designs, negatively impact user experience. Currently, numerous scholars have conducted research in this field, which can be categorized by methodology into field experiments, indoor model experiments, and indoor extended reality experiments.

Field experiments and indoor model experiments were widely used in early research, where participants performed tasks in actual underground structures or scaled-down simulated spaces. Their feedback was collected and analyzed through physiological monitoring devices or questionnaires.(Chirag Deb, 2010; Yang & Jun, 2018, 2019; Yang & Moon, 2018)

However, perception experiments often require modifying environmental variables to study their impact on human responses—something that is difficult to achieve efficiently with traditional field or indoor experiments. As a result, VR/AR technologies have gradually gained attention among researchers, offering a more flexible and controlled experimental environment.

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In VR/AR-related research, crowd evacuation has received significant attention. Researchers typically construct virtual scenarios of underground space where hazards such as fire(S. Lu, M. Rodriguez, Z. Feng, D. Paes, A. B. Daemei, R. Vancetti, S. Mander, T. Mandal, 2025) or earthquake(Mitsuhara, 2024) take place. Participants navigate using omnidirectional treadmills or handheld controllers. These experiments investigate factors such as lighting conditions(Cailing, 2018; Mossberg et al., 2021) and guidance signage(S, 2019; Zhuang et al., 2025) on evacuation efficiency. Some studies focus on behavioral patterns in crowds, such as group coordination (60), while also considering influences like spatial familiarity and individual wayfinding habits(C. Wang et al., 2025). Other scholars have conducted VR wayfinding experiments in daily commuting scenarios, using metrics like navigation time and error rates to propose optimizations for signage systems.(S. Wang et al., 2021) Additionally, VR environments enable rapid feedback on spatial design alternatives. For instance, researchers have modified layouts(Yao et al., 2019) and material interfaces(Sun et al., 2022) in underground shopping streets, analyzing participants' dwell time and subjective preferences to derive design recommendations. In contrast, AR technology has seen relatively limited experimental application, primarily serving as a navigation aid(Demirkan, 2020) to test its effectiveness in real-world scenarios.

Based on the aforementioned review, current VR/AR technologies can effectively assist in constructing highly immersive human-factor experimental environments and conveniently adjusting environmental elements, proving more economical compared to field experiments. However, these methods exhibit the following limitations: the fidelity of scenarios heavily depends on modeling precision, resulting in high modeling costs; subjects are often confined to the vicinity of equipment with limited freedom of movement; and the incorporation of certain environmental elements lacks scientific mechanisms.

This study leverages mixed reality technology to superimpose virtual elements onto real physical environments, effectively reducing modeling workload while enhancing pedestrian mobility. Furthermore, a lightweight and modular human-factor data lifecycle management system was developed to address issues of inconsistent data formats and collaborative analysis difficulties in existing methods. Finally, to overcome the prevalent lack of scientific mechanisms in current research, the proposed framework supports remote integration of external scientific datasets, thereby establishing evidence-based simulation for key environmental parameters.

2. MIXED REALITY

Mixed reality is a technique to deeply combine virtuality and reality in various proportions, making them a continuum(Mann et al., 2018). The concept of mixed reality was firstly put forward by Paul Milgram and Fumio Kishino in 1990s(Milgram & Kishino, 1994), after which is getting increasingly popular, just as virtual reality(VR) and augment reality(AR). However, there are some differences among the three techniques, which means that MR can be considered as a further development of VR and AR.

The distinguishing feature of MR can be demonstrated in the figure below. MR device can perceive depth information in real space, enabling virtual elements to maintain realistic relative positional relationships with real-world objects. In contrast, AR can only overlay two-dimensional virtual "masks" onto real space, where virtual objects merely cover the physical environment without reflecting proper spatial relationships. Meanwhile, in VR technology, the real and virtual worlds are completely disconnected—when users are immersed in the virtual environment, they cannot perceive any information from the real world.

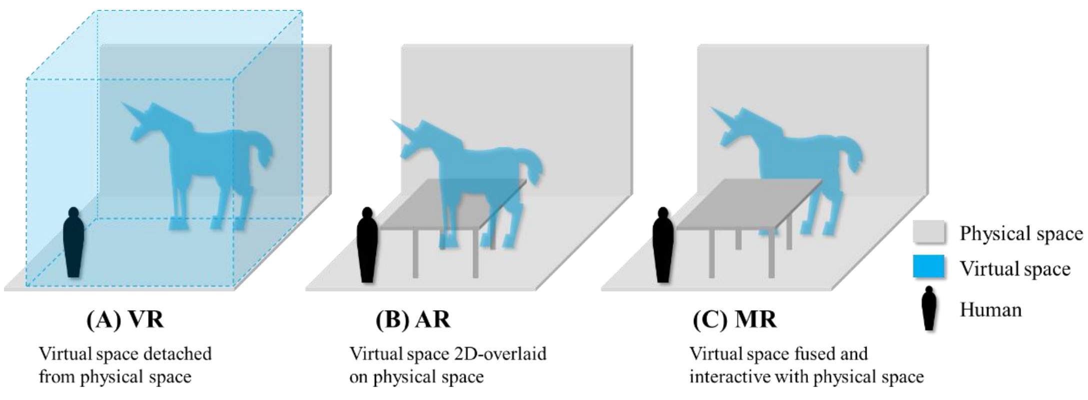


Figure 1. *Comparison among VR, AR and MR*

Based on the above characterastic, MR technique can more effectively utilize existing physical space than AR and VR do. As a result, only limited work is required in virtual modeling to establish highly immersive scenario, which not only reduces modeling cost but also allows users to move freely within the physical space. These advantages have enabled MR to find applications across numerous fields.

In order to reveal the implementation situation of this inspiring technique, 22094 papers are searched from Web of Science by key word MIXED REALITY and dvided into 14 major fields. It is illustrated that MR is widely utilized in computer science, medicine, humanities, and arts. However, the technique sees fewer applications in architecture including underground space. What's more, MR is mainly used as an assistance for the design, construction and managment of architectures, while the application on human perception experiment is relatively insufficient, resulting in a lack of scientifically quantifiable indicators for environmental evaluation. Therefore, in this research MR is used to set up the experiment system for human perception experiment, mainly contributing to construct the experimental scenario. In addition, associated devices such as data collection and managment are also integrated.

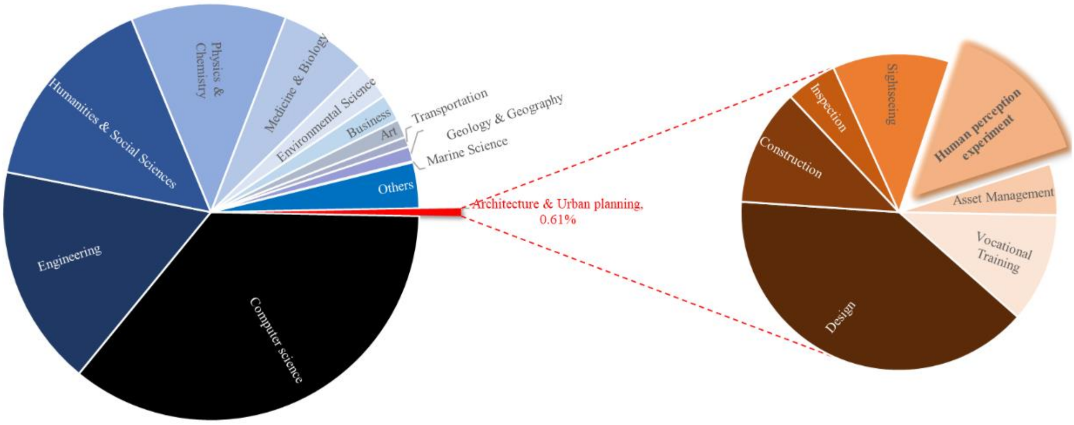


Figure 2. *Application of MR in architecture & Urban planning and other fields*

3. HUMAN PERCEPTION SYSTEM ENHANCED WITH MIXED REALITY

3.1. Framework

The framework consists of MR-based scenario building device, a set of bio-sensors and a data management system. The scenario construction is based on both virtual elements and real-world site to provide an immersive experience, the human response to which will be collected by bio-sensors in the meantime. Aquired data will be transmitted to a management platform for further analysis and real-time display.

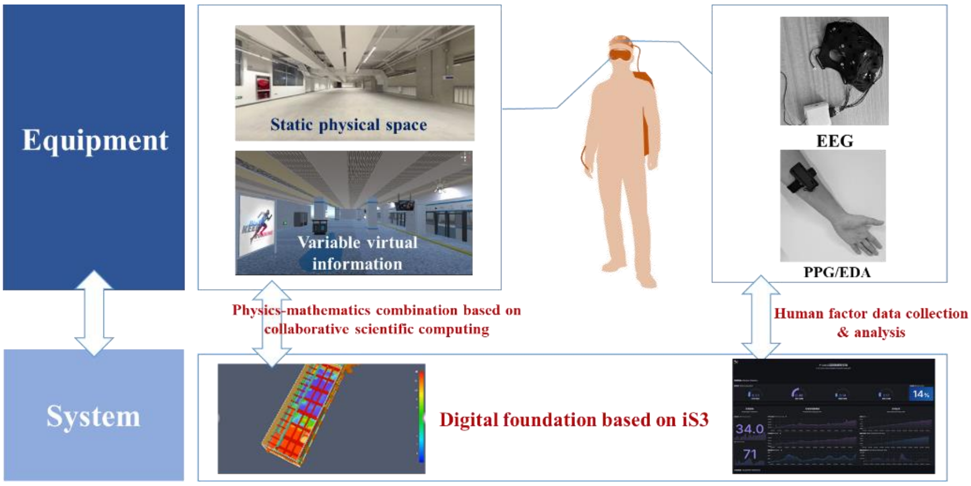


Figure 3. *Framework of equipment system of human perception experiment*

3.2. Scenario building based on MR

The scenario is developed using Unity and displayed by Apple Vision Pro. The 3D information of physical space, including the coordinates of surrounding structural surfaces are sensed by radars on MR helmet, after which the virtual elements will be located on the correct positions as according to the scenario design scheme.

What's more the scenario should be dynamically adjustable in order to effectively investigate the impact of specific environmental factors on participant experience. Therefore, the virtual elements can be controlled by both manual operation and numerical simulation.

The manual control of virtual elements is achieved using Mirror plugin used for multi-players game framework. The experimenter operate the server, while the participant can be considerd as a client. The order of changing the status of virual objects is given by server and transmitted to the participant via KCP protocol.

In addition, some objects can be adjusted according to simulation result for the scientific nature of experiment. The simulation is firstly carried out on software such as Abaqus, FDS, and so on, after which online database will make the data stored and exposes an interface for external requests. During the experiment, the simulation result will be invoked in real-time to dynamically adjust relevant virtual element attributes—such as transparency, position, and velocity, ensuring the object's appearance and motion conform to scientific principles.

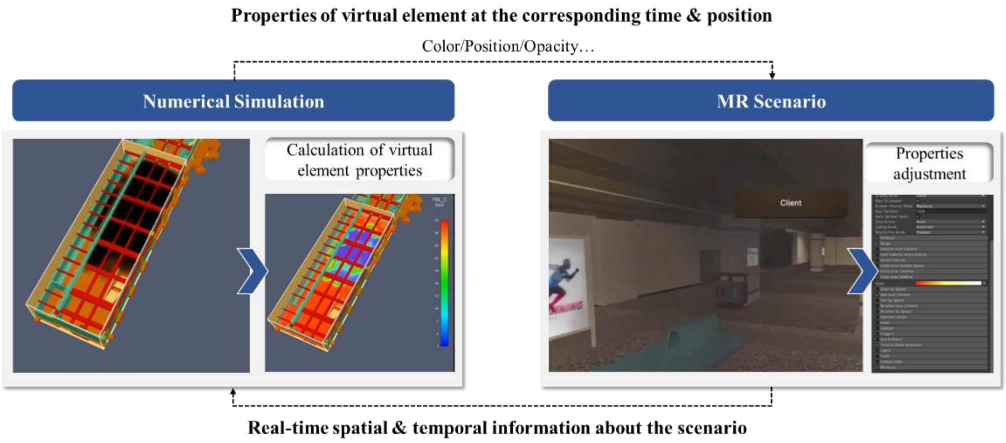


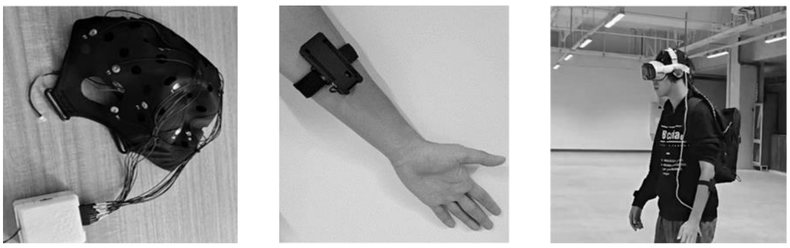
Figure 4. *The integration of scientific mechanism into scenario*

3.3. Physiological data collection

The human response to the scenario can be measured for the quantitative analysis on the dimensions of emotion and cognition activities. A set of wearable devices is developed to measure EEG, EDA and PPG.

The EEG signals are acquired via 3D-printed flexible brush electrodes integrated into an elastic fabric cap, enabling 18-channel EEG wave collection. Through time-domain and frequency-domain analysis, the activity levels of different EEG frequency bands can be identified, reflecting cognitive load and arousal states.

The EDA and PPG sensors are integrated into a single chip. Emotional fluctuations trigger vasoconstriction/vasodilation (affecting blood flow) and sweat gland secretion (altering skin conductance). These changes are captured as EDA and PPG signals, which not only derive basic physiological metrics (e.g., heart rate variability, skin temperature) but also reflect emotional responses.



(a) EEG sensor (b) EDA & PPG sensor (c) participant wearing the sensors

Figure 5. *Wearable bio-sensors*

3.4. Full lifecycle data management

The acquired physiological data is managed by an online platform equipped with database, analysis module and display panel. Both structed and unstructed data can be stored and requested via API for further analysis and presentation.

The intelligent analysis module operates as a microservice that processes raw physiological signals through time-domain and frequency analysis to extract key features, enabling the assessment of emotional states and cognitive activity levels. The default analytical capabilities include emotion composition analysis based on skin conductance level (SCL), heart rate and body temperature conversion derived from PPG, as well as waveform separation and extraction across EEG frequency bands. By integrating these multimodal physiological measurements, the module provides comprehensive insights into both affective and cognitive dimensions of human states. In addition, users can also customize new modules and integrate them into the framework due to its modular architecture and high extensibility.

The data control panel is developed on an open-source framework, offering highly customizable settings that allow users to selectively display key information. This enables real-time monitoring of participants' physiological feedback and preliminary analysis results during experiments.

Figure 6. *Panel for the display of human response data*

4. APPLICATION: FIRE DRILL

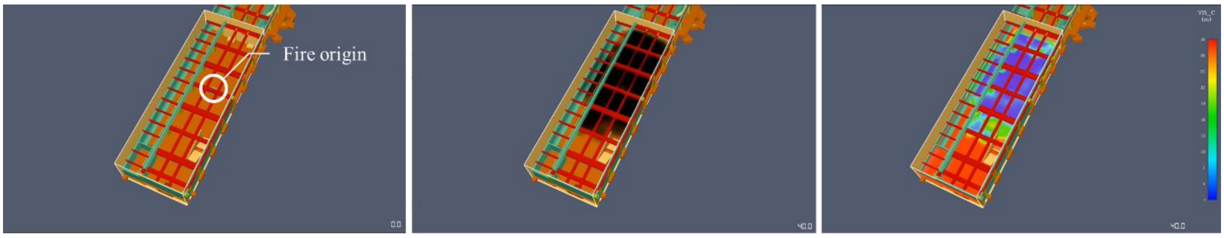
4.1. Scenario building

A MR enhanced fire drill is carried out in a 1:1 railway station section in November 2024, as a preliminary test of the validity of the proposed human perception system. The station section has an area of about 1500 m^2 and a height of 3 m, equipped with typical structural components of subway station such as tunnel and escape staircase(Figure 7(a)). A series of virtual elements, consisting of train, emergency guidance system, main service facilities and some decoration, are modeled by Unity and added to the physical space via MR technique to make the scenario more vivid(Figure 7(b)).

(a) Physical space (b) Mixed reality station (c) Fire scenario

Figure 7. *Scenario building based on the mixture of physical space and virtual elements*

Fire and smoke modeled by particle system will be activated in MR format at a random time after the scenario is loaded, providing an escape scenario with low visibility. In order to endow scientific mechanism of smoke spreading, the opacity of smoke particles at each time step is determined based on fire dynamics simulation(FDS). A full-scaled model of station is built and the fire is assumed to happen at the center of the site(Figure 8(a)).



(a) Scenario for FDS simulation (b) Smoke spreading (c) Visibility at 1.6 m

Figure 8. *FDS for determining the opacity of smoke particles in MR scenario*

In order to quantify the influence of smoke spreading(Figure 8(b)), the dynamically changing visiblity (m) is extracted at the height of 1.6 m, which is close to the eye level when bending over for evacuation(Figure 8(c)). Then the opacity of smoke particles is estimated using the formula below:

$$Opacity(x,y) = 1 - \frac{Vis(x,y)}{Vis_{\max}} \tag{1}$$

where the Vis_{max} (m) is the initial visibility without any smoke, while $Vis(x,y)$ (m) represents the real-time visibility at position (x,y).

A ring of smoke effect is deployed locally around the head of participant. For each frame advance in the scene, the participant's coordinates are transmitted back to the server, after which the corresponding smoke opacity value is calculated through 2D interpolation based on real-time positional data. This dynamically computed value is returned to the client-side and applied to the smoke assets, scientifically reproduces the movement through smoke-filled environment.

4.2. Procedure design

The evacuation procedure is designed as the figure below. After wearing experiment equipment and receiving brief training, the participant opens the evacuation application and complete scenario loading. A short period of time is required to get adapted to the virtual-physical hybrid railway station, after which the formal evacuation begins. Participants will try to reach exit within a maximum of 90 seconds before their evacuation performance is evaluated.

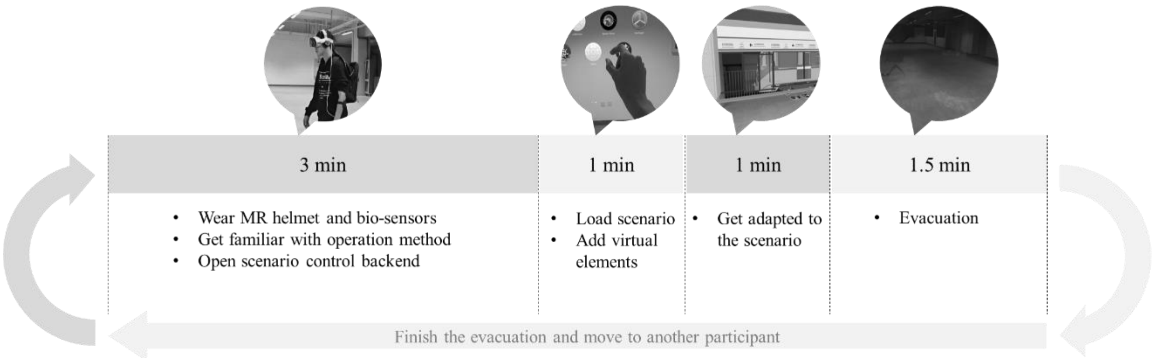


Figure 9. *Procedure of fire drill*

4.3. Performance evaluation

Time consumption is the main evaluation standard. The Chinese Code for Design of Metro (GB50157-2013) is refered where the permissible evacuation time is 6 min. However, the allowable time is adjusted to 90 s in this study, considering the limited spatial complexity and relatively low evacuation difficulty. If participants reach the exit within this timeframe, the system registers a successful evacuation and displays their escape time in a pop-up window from the first-person perspective. Otherwise, the attempt is recorded as a failure. Physiological data collected during the evacuation process can also be analyzed to assess emotional and cognitive states, providing explanatory insights into the evacuation outcomes. But in this stage this part of data still wait for further analysis.

5. CONCLUSION

An equipment system for human perception experiment in underground space is developed and enhanced with mixed reality. Virtual elements are overlaid onto physical environments based on spatial computing to built a highly immersive experimental space, where scientific simulation result can be leveraged to scientize some key elements. The human-factor data can be collected and management in a platform for further analysis.

Fire drill design in a subway station is discussed as an application of this system. It is demonstrated that the equipment is able to build vivid experimental envirionment with modeling cost reduced. The human response is recorded and can be used as a powerful supplement for subjective evaluation in the further analysis.

In the future, it would be advisable to develop real-time interaction mechanisms between crowd simulation and MR experiments to enhance scenario realism. Additionally, an experimental framework capable of supporting multiple participants should be established to enable collaborative analysis of feedback from different test groups, thereby improving the reference value of the results.

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