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BuildEnVR: An Immersive Analysis System for Environmental Field

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***Abstract*—Amidst global warming and escalating extreme weather events, indoor environmental quality's impact on human health and public hygiene gains prominence. Environmental parameters exist essentially as fields, which are characterized by high dimensionality, density and complexity, and contain massive amounts of information in space. To facilitate visualization and analysis of indoor environmental field, we design and implement BuildEnVR, an immersive analysis system by virtual reality, enabling remote analysis of real-time and historical environmental field data. Grounded in user needs and cognitive psychology, three visualization modes emerge: the Virtual Sensor mode enables users to access perceptual data in real-time at any 3D coordinates in ambient space, the 4D Heatmap mode visualizes spatial variations and trends over time in environmental field data, and the Synaesthesia mode realizes the fusion display of multi-dimensional environmental field data, allowing users to quickly understand the overall condition of the indoor environment with a low cognitive load. Extensive user surveys validate BuildEnVR's intuitiveness and precision, and it is suitable for both experts and general users.**

***Index Terms*—virtual reality, immersive analysis, internet of things, interactive design**

I. INTRODUCTION

Effective indoor environmental conditions play a critical role in ensuring human well-being, particularly in the context of severe climate conditions resulting from global warming and frequent extreme weather events. It is estimated that approximately 80% of an individual's lifetime is spent indoors [1]. Within indoor spaces, numerous environmental parameters significantly impact human health, including factors such as temperature, humidity, illuminance, carbon dioxide (CO_2) concentration, and particulate matter (PM2.5) levels. In the case of open-plan spaces like offices, where multiple end-user devices are present, the distribution of these environmental parameters within the space exhibits substantial variations. This leads to heterogeneous environmental conditions within the same room, posing challenges for users.

Therefore, there are increasing need for a feature-rich indoor environmental parameters analysis and visualization tool. Different from other data types, environments parameters exist essentially as fields, which are characterized by high dimensionality, density and complexity, and contain massive amounts of information in space. Traditional approaches primarily present data in the form of airflow streamlines [2], line charts [3], heatmaps [4] [5] etc. These methods, however, usually display environmental parameters in a 2D screen [6], whereas the actual measured space is a three-dimensional structure, leading to potential discrepancies between space and data.

In recent years, with the maturation of virtual reality (VR) and augmented reality (AR) technologies and the widespread use of head-mounted displays (HMDs), researchers can engage in the domain of immersive analysis [7], which leads users to analyze daily data like office data and motion data in a virtual and immersive environment [8]. With VR and AR, immersive environments enable users to intuitively align environmental fields with the physical space, offering an opportunity to better understand the environmental field data [9] [10] [11]. Besides, the development and deployment of wireless environmental parameter sensors in architectural spaces have facilitated the real-time distribution of environmental data [12].

Nonetheless, existing approaches still have some limitations and may not adequately address the diverse requirements in practical applications. First, prevailing environmental visualization methods predominantly offer monotonous presentation [13]. Second, existing approaches frequently focus on showcasing offline or simulated data [14] [10], rather than enabling real-time environmental field perception, visualization, and analysis. Third, conventional methods typically present only a single dimension of data at a given time [15], failing to provide users with a holistic understanding of the indoor environmental conditions. Last, the issue of users' cognitive load is not emphasized by existing methods, so it is difficult for users to quickly visualize the overall state of the environment with low cognitive load.

To address these challenges, in this study, we propose BuildEnVR, a VR-based immersive analysis system for architectural environmental fields. BuildEnVR connects in real-time

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with wireless sensor data from iBEMs (intelligent building environmental monitor [16]), enabling the acquisition of real-time indoor environmental data. Based on theories related to cognitive psychology, we propose a synaesthesia visualization technique that simultaneously integrates and displays multi-modal environmental field data to allow users to intuitively understand the overall state of the environment. To accommodate diverse user groups and requirements, the system offers three immersive analysis modes: Virtual Sensor Mode, 4D Heatmap Mode and Synaesthesia Mode. The Virtual Sensor Mode caters to professionals, where VR controllers are developed as virtual sensors that provide real-time values at any point within the architectural environmental field. In 4D Heatmap Mode, we enhance traditional 2D heatmaps by incorporating 3D meshes and temporal dimension. This mode allows users to watch the spatial distribution and evolutionary trend of field data over time. The Synaesthesia Mode facilitates the simultaneous display of multidimensional environmental field data. In this mode, we generate a desk miniature synaesthetic landscape called DMS-Landscape to integrate multiple environmental field data in a synaesthetic way. We merge environmental field data from five different parameters (temperature, humidity, illuminance, CO_2 and PM2.5), enabling users to visually perceive the environmental field's state resulting from the synthesis of multidimensional data, thus providing an intuitive and rapid understanding of the environmental conditions. Finally, user surveys and expert feedback demonstrate that BuildEnVR significantly reduces users' cognitive load and enhances the amount of information users can acquire during immersive analysis of architectural environmental fields.

In summary, our contributions are:

- Designing and implementing an immersive analysis system for visualizing indoor environmental field data in architectural settings.
- Achieving real-time indoor environment sensing as well as data visualization through integrating iBEM, a wireless environmental sensor with VR environments.
- Based on relevant cognitive psychology theories, we present three distinct environmental field data analysis modes which fulfills a wide variety of user requirements.
- Conducting user surveys and analyses of BuildEnVR, and the results verify its usability and effectiveness.

II. RELATED WORK

A. Implementation in Immersive Analysis

VR and AR offer novel and user-friendly immersive experiences for data visualization, making immersive analytics a prominent research domain [17] [18]. This approach finds application across diverse data types requiring interactive manipulation in daily activities .

Notably, office data and charts have been extensively examined in immersive analytics studies. Several investigations strive to enhance or supplant conventional 2D displays by utilizing XR to analyze office charts and graphs within a 3D spatial context [19]. This advancement contributes to heightened efficiency and improved correlation in processing office chart data. The presentation of temporal and spatial data is another topic in immersive analytics [20]. VRGit anchors the History Graph to the controller, making it easy for users to compare different chronological versions [21].

The above studies mention that the utilization of 3D space for immersive analysis can improve the user's understanding of multidimensional data and can reduce the user's cognitive load compared to non-immersive analysis. These findings provide valuable suggestions for the design of BuildEnVR.

B. Immersive Visualization on Indoor Environmental Fields

Environmental field data inherently possesses spatial properties, with each parameter point within an environmental field having distinct spatial coordinates. This spatial dimension adds complexity to the task of comprehending field data, both for users and researchers. Presently, heatmaps are commonly employed by scholars and developers as the primary means of representing field data [22]. Heatmaps' utility lies in their ability to visually convey numerical distinctions in environmental parameters through color variations. However, it's essential to acknowledge the limitations of heatmaps. They excel at depicting numerical values of environmental fields but fall short in establishing an effective link between field data and its spatial environment. In response to this challenge, immersive analytics emerges as a promising avenue for environmental field visualization. By leveraging the user's surrounding space, immersive analytics holds the potential to alleviate cognitive load and enhance the understanding of spatially-oriented environmental data.

The integration of XR with architectural environmental field visualization has a long history. As early as 2005, Ali et al. utilized AR-HMD to display heatmaps representing spatial temperature profiles [9]. In recent years, with the development and improvement of XR devices [23], Tomihiro et al. proposed a method that representing temperature fields and airflow patterns through heatmaps and colored lines respectively [11]. Lin simplified field data processing, enhancing efficiency in immersive analysis [6]. Some studies have attempted to achieve real-time data representation and lightweight calculations for immersive analysis. Chae et al. proposed a client-server model in AR to provide real-time room airflow information on mobile devices [15]. Similarly, Wei et al. used mobile devices to present airflow trajectories in the form of particle clusters [24].

However, these studies primarily focus on presenting the results of field data, with a relatively limited range of data types, such as temperature and airflow, but fail to effectively convey a comprehensive environmental field situation or evaluate and analyze localized environmental parameters. This issue results in unmet requirements for professional users and an excessive cognitive load for non-professional users. BuildEnVR is committed to presenting various types of environmental fields within indoor environments and delivering environmental field information in more comprehensible visual formats, thereby reducing users' cognitive burdens.

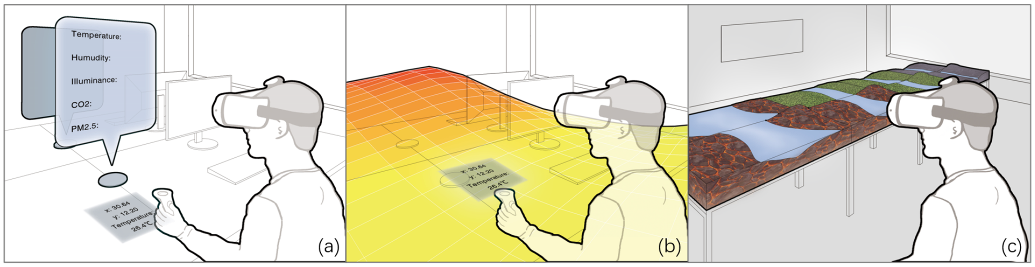

Fig. 1. Three visualization modes of BuildEnVR: (a)Virtual Sensor Mode (b)Heatmap Mode (c)Synaesthesia Mode

III. DESIGN AND IMPLEMENTATION

A. *User-Centric Visualization Design*

Indoor environmental field data is characterized by high dimensionality, density, and complexity, containing vast amounts of information, thus it requires appropriate data visualization methods to effectively represent environmental field data in immersive analysis.

In the field of psychology, users' reading and analysis of data can be viewed as a form of cognitive load [25], where excessive cognitive load can lead to a decrease in learners' work efficiency and accuracy. Therefore, one of the primary goal of BuildEnVR's visual design is to reduce users' cognitive load in understanding architectural environmental fields and enhance cognitive capabilities.

According to the principle of spatial contiguity [26] [27], designers can facilitate learning by placing related information together [25] [28]. Furthermore, dual coding theory suggests that information obtained from images is more effective than text because images can be encoded in both visual and semantic forms [29].

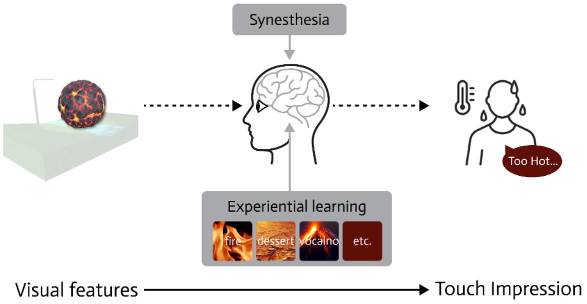

Fig. 2. Synaesthesia design integrates human vision, experience, association ability and touch impression

Additionally, visual information can stimulate users' associations and imagination through multisensory perception, such as visual-tactile cross-modal perception [30]. This theory provide us insight that visual effect of object can be transformed into human feelings such as temperatue and humidity (Figure 2).

The inspiration drawn from the above is that if environmental field data encompasses various types of information such as temperature, illuminance, and gas concentrations, then integrating these pieces of information coherently within a single interface might facilitate users in accessing environmental field information. Additionally, environmental field data should be presented in visual patterns as much as possible, minimizing textual representations within the users' field of view.

B. *Immersive Analysis Modes Design*

Based on the results obtained from relevant literature in cognitive psychology, we design the following three visualization modes in BuildEnVR to visualize indoor environomental fields immersively, efficiently and accurately.

1) Virtual Sensor Mode: We have developed the Virtual Sensor Mode for viewing and analysing interpolated environmental field data and raw sensor values (Figure 1a). In our design the left-hand VR controller is transformed into a real-time updating numerical panel. The system tracks the controller's spatial position to display the corresponding environmental field values. Users can select to show environmental parameter types using a dropdown. As the controller moves, the displayed environmental field values and coordinate values on the panel also change. Besides, The data from several real sensors are also incorporated into the VR environment from the real-world setting.

2) 3D & 4D Heatmap Mode: The Heatmap Mode presents users with 3D and 4D heatmaps corresponding to a specific moment in time (Figure 1b). In addition to color, the height of the 3D and 4D heatmaps is associated with environmental values, encoding changes in environmental data both in color and vertical elevation. The 3D heatmaps align with the building model, allowing users to immerse themselves within the heatmaps for an in-depth environmental analysis. All five environmental parameters are available in the 3D heatmap format.

The 4D heatmap, resembling a tidal ebb and flow effect in a virtual environment, adds a temporal dimension to the 3D heatmap, dynamically illustrating trends in environmental data over a specific time frame. This mode assists users in identifying environmental field data changes over the course of a day, a month, or even a year.

In comparison to 2D screens, VR offer an immersive experience. 3D and 4D heatmaps capitalize on their high discernibil-

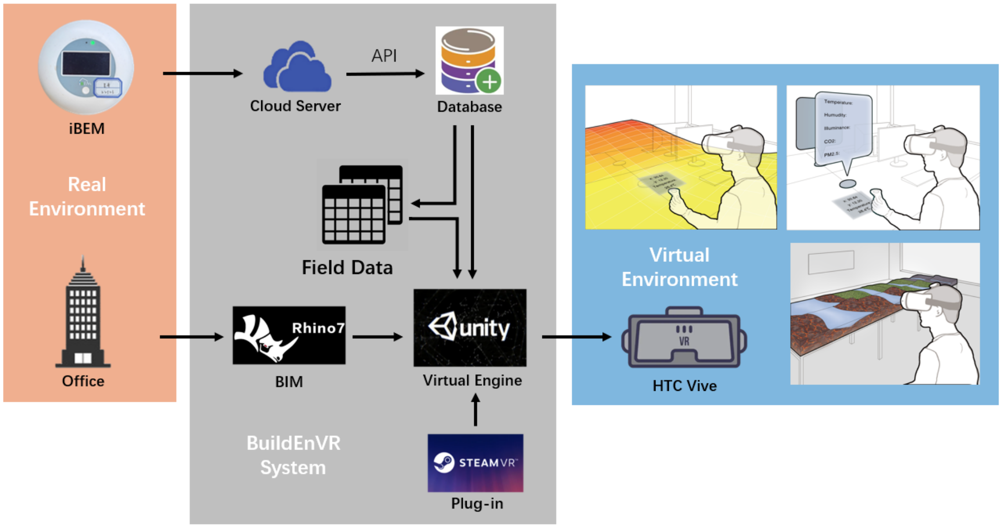

Fig. 3. BuildEnVR environment consists of BuildEnVR system, iBEM platform, real environment and virtual environment.

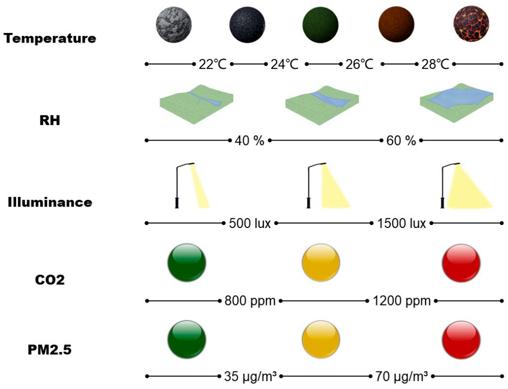

Fig. 4. The mapping of DMS-Landscape

ity within immersive settings, significantly reducing occlusion issues associated with height differences. It is beneficial for both professional researchers and general users to utilize this mode for environmental data analysis.

3) Synaesthesia Mode: We attempted to address the issue of users facing excessive cognitive load when simultaneously viewing multiple environmental parameters by introducing a Synaesthesia Mode according to the visual-tactile cross-modal perception [30]. This mode integrates information from the five environmental parameters and presents the assessed environmental field information to users in an imaginative and synaesthetic manner (Figure 4). We decided to implement the concept of the Synaesthesia Mode by building the desktop miniature synaesthetic landscapes(DMS-Landscape)(Figure 5c). For example, the temperature parameter in the central of the landscape are associated to the land's type (stone, grass, lava etc.) and the humidity parameter are associated to the river's width.

Figure 4 illustrates the visual effects of the Synaesthesia Mode design. The five environmental parameters correspond to five modules in the DMS-Landscape, each distinguished by color and texture. Temperature is associated with the material ”land,” humidity is correlated with the width of the ”river,” illuminance is linked to the brightness of the ”streetlamp,” while carbon dioxide concentration and PM2.5 concentration are represented by circular colors on signs. We divided temperature values into five categories: cold, cool, moderate, warm, and hot. As the human sensitivity to other parameters is lower compared to temperature, the values of other environmental parameters were categorized into three levels.Each DMS-landscape corresponds to a workspace. When the Synaesthesia is activated, the system calculates the environmental parameters at the center of each workspace.

IV. IMPLEMENTATION

We constructed the BuildEnVR immersive analytical environment to operationalize the psychological theoretical analysis and feature design pertaining to environmental field visualization mentioned above. As shown in figure 3, BuildEnVR integrate sensors, cloud server, field data analysis program, virtual engine and VR environment. Its workflow is to acquire environmental parameters by iBEMs in the beginning. After that, BuildEnVR system visits and downloads iBEM data from iBEM platform and then generates environmental field data. In virtual engine, field data is aligned with building information model (BIM) by scripts and plug-in. Finally, after the integration, Three visualization modes are presented in VR. BuildEnVR currently includes five environmental parameters, namely temperature, humidity, illuminance, CO_2 concentration, and PM2.5 concentration, as data types for immersive visualization of the environmental field. These five types of

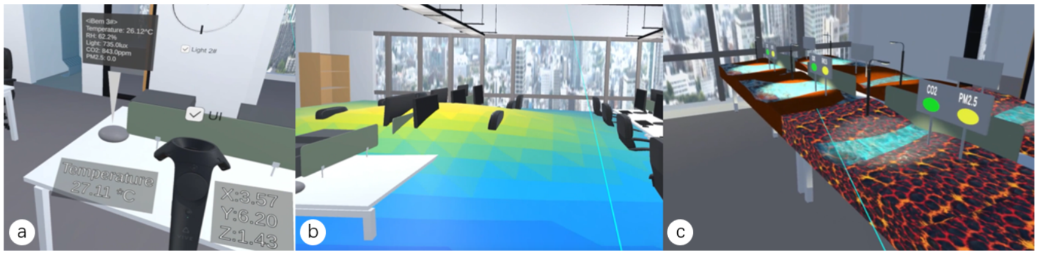

Fig. 5. Modes in virtual scenes when users experienced for themselves: (a) Virtual Sensor Mode, (b) 4D Heatmap Mode, (c) Synaesthesia Mode

environmental parameters are representative and collectively reflect users' sensory perceptions (temperature, humidity), visual experiences (illuminance), and indoor air quality (CO_2 concentration, PM2.5 concentration).

A. Software and Platform

We employed the Unity3D engine[1] for the development of BuildEnVR and selected the HTC Vive Cosmos Elite headset package[2] as the VR hardware equipment. Additionally, the design of VR scenes was facilitated through HTC's HTC.UnityPlugin plugin. BuildEnVR utilizes this plugin for the control of HMD and controllers, enabling features such as teleportation and laser-based selection within the VR environment.

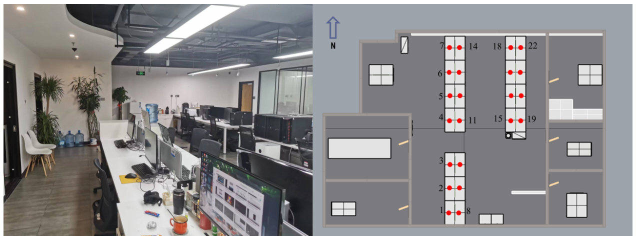

Fig. 6. Experimental site and floor plan

B. Virtual Space Construction

The experimental space comprises an office space with dimensions of 7.8 by 11.2 meters (Figure 6). This office space accommodates 22 workspaces, and we consider its size and occupancy representative of typical office buildings. A proportional model of the building was constructed using modeling software, with a focus on accurately replicating the dimensions and layout of the real space.

C. Interaction with Sensor and Data Analysis

We employed the iBEM device developed by Lin et al. [16] for environmental sensing within the indoor environment. iBEM is a well-established sensor for building environmental parameters (Figure 3) and has been extensively used in over 100 buildings. It integrates sensors for temperature, humidity, illuminance, CO_2 concentration, and PM2.5 concentration (Table I).The wireless data transmission and cloud platform storage capabilities were primary considerations for utilizing iBEM. This enables immersive real-time visualization of environmental parameters in BuildEnVR.

TABLE I
INFORMATION ON IBEM'S SENSORS

Parameter	Range	Accuracy
Temperature	-40-80 °C	±0.5 °C
Relative humidity	0-99%	±5%
Illuminance	0–50000 lx	±5%
CO_2	0–5000 ppm	±75ppm
PM2.5	0–1000 μ g/m^3	±10%

Nine iBEMs were evenly distributed on desks within the area of personnel activity to enhance the accuracy of sensor measurements within this region. The system recorded environmental parameters, data acquisition timestamps, and spatial coordinates for each iBEM. Subsequently, spatial interpolation algorithms were employed to interpolate discrete individual environmental parameters. After fine-tuning and analysis, the interpolation data were calculated with a step size of 0.1 meters for displaying data information and a step size of 0.3 meters for generating heatmaps. This approach ensured maximum precision while avoiding frame drops and stuttering.

D. Immersive field data analysis

BuildEnVR supports users in visualizing both real-time and historical data. When users select to view real-time data, the system will send access request to the cloud server to obtain the real-time data, and then using interpolated method to generate the field data, which is the basis of the visualization modes. the system offers three immersive analysis features: Virtual sensor presentation, 3D Heatmap presentation of environmental fields, and personnel workspace synaesthetic evaluation visualization, referred to as the Virtual Sensor Mode (Figure 5a), 3D Heatmap Mode (Figure 5b), and Synaesthesia Mode (Figure 5c), respectively. Historical data encompasses the Virtual Sensor and 3D Heatmap modes, with the addition of the 4D Heatmap mode.

The design of the user interface (UI) panel considers the logical flow of user engagement in immersive analysis. The initial interface provides two options: real-time data and historical data (Figure 5). By clicking on either real-time data or

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[1] https://unity.com/

[2] https://www.vive.com/cn/product/vive-cosmos-elite/overview/

historical data, users enter the respective interface, allowing them to choose visualization modes by using UI components such as toggles and dropdowns.

V. PROFICIENT EVALUATION AND USER STUDY

A. User study with non-proficient users

TABLE II
INFORMATION OF PARTICIPANTS

Number	Gender	Familiarity
1	female	frequent use of VR
2	male	frequent use of VR
3	male	heard of VR
4	male	have used VR
5	male	have used VR
6	male	heard of VR
7	female	have used VR
8	male	have used VR
9	female	frequent use of VR
10	female	have used VR

1) Participants: Ten participants (4 female, 6 male), aged 21 to 30, took part in the usablity test. All participants possessed a level of familiarity with VR, although none had technical expertise. Further participant demographic information is available in table II.

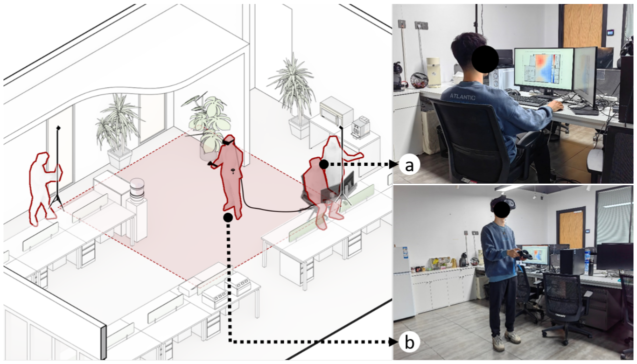

Fig. 7. Viewing heatmaps in the sight of (a) PC group and (b) VR group

2) Experiment design: Participants were asked to perform specific environmental assessment tasks using both our VR system and traditional PC methods in two scenarios (Figure 7. To account for learning effects, we prepared two sets of environmental data and controlled for the sequence of using VR or traditional methods as block variables. In each experiment, we measured three variables: completion time, subjective cognitive load reported using the NASA-TLX scale [31], and system satisfaction as rated by participants.

The details of 2 scenarios are described as following.

Scenario 1: Locating the extremum of a single environmental indicator.

Participants were tasked with identifying the extreme point of a specific environmental indicator, including its value and horizontal coordinates, to locate outliers (e.g., unusually high temperatures) for further cause analysis. In the VR method, participants activated the 3D Heatmap function of BuildEnVR, identified the highest and darkest area, and moved towards it to determine the exact value and coordinates using the Real-time Positional Data Display on the controller hover panel. In the PC group, participants used a 2D heatmap on a PC display. Upon task completion, participants reported the extreme value and its location to the researchers.

Scenario 2: Integrating five environmental indicators to identify the seat with the poorest environmental quality.

Participants evaluated the overall environmental quality of a single seat, considering five dimensions. Using the VR methodology, participants primarily utilized the Synaesthesia mode. They started in one corner of the virtual space, activated the Synaesthesia mode, and assessed the environmental quality based on visual attributes such as patterns and colors in the DMS-landscape (Figure 4. Evaluation scales for the five environmental indicators were provided prior to the task. In the PC group, participants used five parallel thermal images and a flat map for spatial information, simulating typical visual data from mathematical drawings and thermal simulation software. Participants in both groups identified the seat with the poorest environmental quality and explained their choice.

B. Evaluation with experts

1) Interview: To assess the professional usability of BuildEnVR, we shared demonstration videos of BuildEnVR with five expert participants who are professor or PhD student in the department of Built Environment. These videos showcased each visualization feature of BuildEnVR. After viewing the demonstration videos, experts were asked to provide subjective responses.

2) Feedback: Experts responded positively to BuildEnVR, acknowledging that the integration of the environment field with VR environments created a highly immersive experience. They believed that this immersive environment greatly aided users in comprehending the spatial and environmental aspects. From a holistic perspective, BuildEnVR's presentation of real-time and historical data, along with the design of four visualization modes, ensured the system's applicability across diverse scenarios and user groups.

Several experts also provided constructive feedback. E2 suggested, "While Heatmap Mode allows users to immerse themselves in the surveyed space, it may be beneficial to incorporate miniature models of the surveyed space at appropriate locations. Simultaneously visualizing the heatmap within the miniature model might enhance users' global understanding of the spatial environmental field."

VI. DISCUSSION AND FUTURE WORK

A. Result analysis

The result of user study is shown in figure 8, which represents the situation of cognitive load in scenario 1 (the above one) and scenario 2 (the below one).

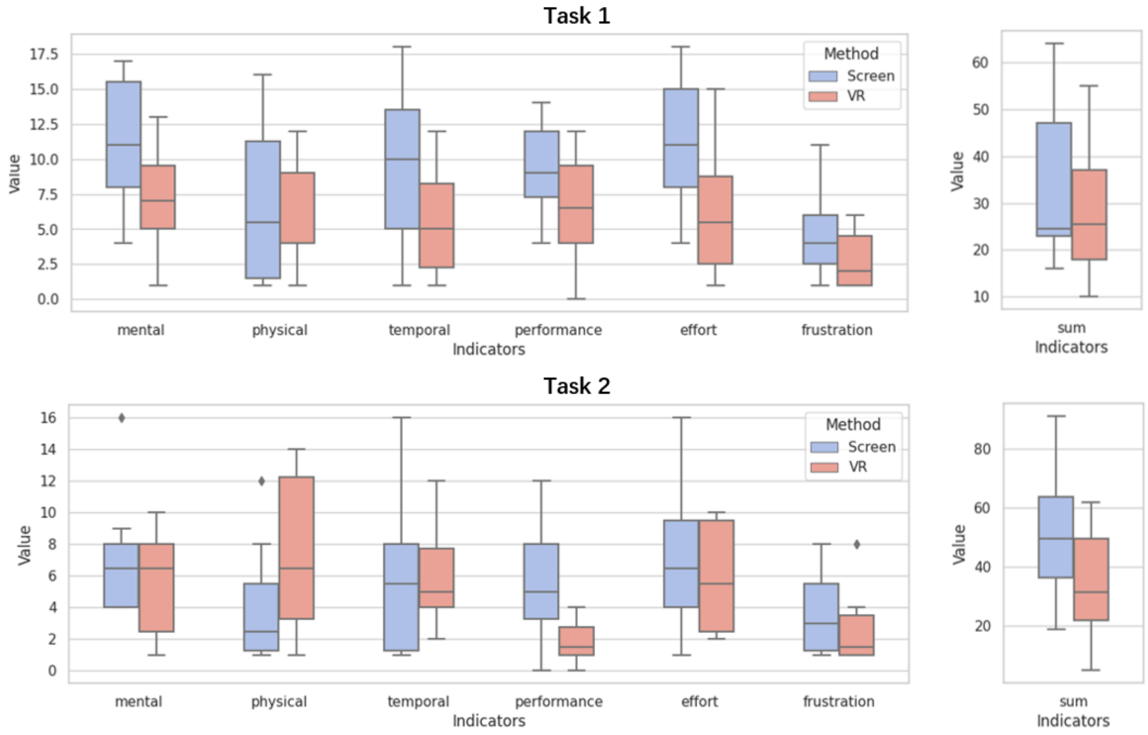

Fig. 8. Result of cognitive load under TLX metrics

1) Completion time: In senario1, participants appeared to have no statistically significant difference between using VR method and traditional PC methods. For data collected in Senario 2, we conducted paired t-test and recieved t = 3.088, p = 0.015<0.05, indicating the difference to be significant. On average, VR method saved 16.44 seconds for each user compared to PC when performing the enviornmental assement task.

2) Subjective cognitive load reported using the NASA-TLX scale: The NASA-TLX (Task Load Index) is a widely-used subjective assessment tool that measures perceived workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration [31]. Higher scores indicate greater cognitive load experienced by users.

The box plots shown in figure 8, display subjective cognitive load evaluations using the NASA-TLX scale for two tasks, comparing VR (red) and traditional screen methods (blue). Notably, In both tasks, VR generally resulted in higher physical and effort demands but lower frustration levels and better perceived performance compared to the screen method. Though the difference in Task 1 is not substantial, the overall cognitive load for VR is consistently lower across both tasks.

B. Future work

The conception of future work is derived from the results of user research and expert opinions. During the user experiments, we observed that users were immersing themselves in the spatial analysis of the environmental field, resulting in a lack of a global perspective to observe the overall environmental field. While this issue is less prominent in office-scale architectural spaces, it could significantly impact the user's immersive analysis experience and efficiency in scenarios involving large-scale architectural applications. This potential issue was also identified by experts. We will consider the experts' suggestions by implementing a miniature spatial map with user's position on the VR controller panel. We believe that this approach represents a promising solution to address this issue effectively.

Besides, a lighter and more convenient hardware device should be considered to make BuildEnVR used widespread. Mobile phone is an appropriate device to achieve AR-based immersive analysis, which can not achieve remote visualization but can reduce the dependency of relatively expensive VR instruments.

VII. CONCLUSION

In conclusion, we have introduced BuildEnVR, an immersive analysis system designed to enhance environmental field visualization in the context of global climate concerns. This work explores a novel interdisciplinary research area by combining VR with indoor environmental fields, incorporating cognitive psychology-related theories to aid in the design of visualization features, and connecting wireless environmental parameter sensors (iBEM) with an immersive environment.

Our contributions include the development of an immersive analysis system, the introduction of 3D heatmaps to the field of environmental field visualization, the pioneering of the Synaesthesia Mode utilizing cognitive psychology theories to reduce users' cognitive load, and the validation of the usability of this research through the user study. User study and expert feedback confirm that BuildEnVR significantly reduces cognitive load, improves accuracy, and reduces cognitive time in certain tasks.

Looking forward, we envision that BuildEnVR can be applied to a variety of complex architectural scenarios, such as office building, public building, museum and specific factory and so on, serving as a feasible solution to address climate concerns, energy consumption problem and uphold public health and well-being.

VIII. ACKNOWLEDGMENT

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