A Virtual Reality-Based Tool with Human Behavior Measurement and Analysis for Feedback Design of the Indoor Light Environment

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Abstract. Human behavior data provides essential feedback information for architects to improve a human-centered indoor light environment design. However, architects have difficulty capturing the complex, multidimensional, and unpredictable behavior of humans, often struggle to get users' feedback on time in the schematic phase. This paper proposes a new virtual reality-based behavioral measurement and assessment tool that quantitatively collects and analyzes individual behavioral data, including travel trajectory, travel time, and gaze points, to reveal user experience and interaction of light, aiming to better help architects get timely feedback from users and create human-centered indoor light environment designs in the scheme optimization phase. To showcase this tool, we utilize an exhibition hall of a museum design as an illustrative example. The experiment demonstrates the feasibility of the proposed tool, and its results suggest that different lighting schemes influence human behavior patterns and that the introduction of natural light usually stimulates more movement. The developed virtual reality tool prototype provides valuable visual information and statistics for analyzing human behavior and evaluating indoor light environment design schemes.

Keywords: Virtual reality · Human behavior · Behavior tracking · Feedback design · Scheme evaluation · Indoor light environment

1 Introduction

Human behavior data is essential feedback information for architects to provide and improve a human-centered indoor light environment design [9]. If the complex, multidimensional, and unpredictable human behavior in indoor spaces can be accurately captured before a building is constructed, it will provide architects with efficient context-based behavioral feedback information and alleviate the architects' labor for light environment design optimization [5]. Therefore, measuring and analyzing the interaction of user behavior with the light environment in building interior spaces has long been an important challenge affecting stakeholder engagement.

© The Author(s) 2023
P. F. Yuan et al. (eds.), *Hybrid Intelligence*, Computational Design and Robotic Fabrication,
https://doi.org/10.1007/978-981-19-8637-6_16

Previous studies on human behavior analysis used multi-agent-based behavioral simulation and field observation using manual labor or monitoring techniques (e.g., camera, Wi-Fi, UWB, Bluetooth) [10]. They either fail to simulate realistic complex and fine-grained behavior or require strict field experiments, rely on a physically built environment, and are challenging to use in the schematic design phase. Recent emerging virtual reality technology has revealed the possibility of overcoming the previous limit, providing individuals an immersed interactive virtual environment that is highly similar to real [2]. For one, highly experimental controlled VR not only allows for rapid construction and modification of virtual scenes but also for the automatic collection of more accurate behavioral data [6]. For another, flexible control of experimental sites and time expands the VR experiment data sample and increases sampling heterogeneity [3]. Specifically, by controlling light factors related to human behavior in the virtual environment, designers can measure behavioral responses for quantitative analysis, an important source of data for the optimization stage of a -centered indoor light environment design.

Taking these advantages, this paper proposes a new VR-based behavioral measurement and assessment tool that quantitatively collects and analyzes individual behavioral data, including travel trajectory, travel time, and gaze points, to reveal user experience and interaction of light, aiming to better help architects create user-centered indoor light environment designs in the scheme of design and optimization phase. This new VR tool provides a platform for participants to freely roam through multiple virtual indoor light environment scenarios while recording their movements and views at high speed and accuracy. Combining real-time realistic rendering in this tool, designers could obtain accurate participants' immersed feedback and their behavioral interaction data in a close to the realistic indoor light environment.

2 Methodology

The workflow for feedback design using the proposed VR-based system is divided into five steps (Fig. 1). First, architectural models and lighting settings are prepared in 3D modeling software. Second, this design content is converted into a realistic-rendered VR environment using the proposed VR system. Then, volunteers are recruited to use head-mounted display (HMD) devices to experience the immersive virtual environment with the design content. Next, users provide their VR feedback through questionnaires, and the behavioral analysis results are obtained from the proposed VR system. Finally, with user feedback, architects can optimize their designs to accommodate user preferences and needs.

The experimental building is modeled in 3D modeling software (e.g., Revit). The model contains the basic structure of the architectural space, including walls, floors, ceilings, columns, windows, furniture, etc. The lighting setup is commissioned in 3D modeling software (e.g. 3dmax) to simulate a realistic light environment. All this information can be exported as an FBX file and then imported into the Game engine (e.g. Unity) [4].

The proposed VR system is designed to record information about the user's behavior in a virtual scene as close to reality as possible, including travel trajectory, travel time, and gaze points. To achieve this aim, first, when importing the 3d model into Unity,

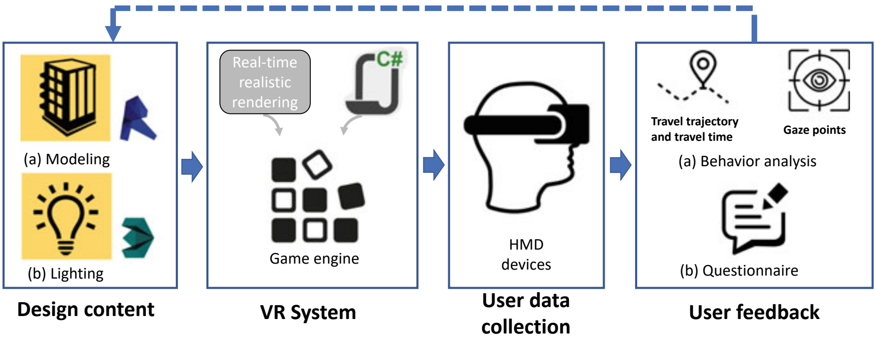


Fig. 1. Workflow of feedback design using the proposed VR-based system.

we use a rendering module (e.g., Universal Render Pipeline (URP)) to add missing information such as material types and properties (e.g., reflections, shadows, etc.) to create an immersive virtual space and achieve real-time realistic rendering. Second, we write code in Unity to record information about the participants' behavioral data and then write visualization scripts to show the results of the behaviors in the building layout.

The data collection contains behavior data from the VR system and subjective data from the questionnaire. For the former, as the participant roams through the virtual scene using the HMD device, the participant's position, head rotation, and timestamp in milliseconds are recorded in Unity. Also, the coordinates of the participant in space and the coordinates of the point where the participant's line of sight intersects with the spatial entity are obtained based on these data. Thus, the system collects three types of behavioral data: travel trajectory, travel time, and gaze point. By visualization scripts, these behavioral data can be displayed directly in the building layout from different views.

Since human feedback to the light environment is a complex cognitive process that requires a combination of multiple evaluation results to be predicted [7]. Therefore, in the proposed workflow, in addition to the measurement of human behavioral information by the proposed VR system, we also employ some traditional scales and questionnaires together. The proposed VR system can measure implicit visual physiological data, the questionnaire can assess the overall experience of the VR system, and the positive and negative affect scale (PANAS) can assess the emotional behavior of the participants [7].

The apparatus in this study include an HMD system (HTC-Vive 2016) and a desktop computer. In the experiment, participants will remain in a standing position and can move forward, backward, left, and right through the experimental scene at a speed of 1.25 m per second via the controller of the HTC-Vive (Fig. 2). The display resolution for both eyes was 2160*1200 pixels and the display screen refresh rate of 90 Hz.

The procedure of the experiment consists of five parts:

- Preparing experimental scenarios of the different indoor light environments in the same model.
- Introducing the overview of the experiment to the participants and making sure they are acquainted with the HMD device.

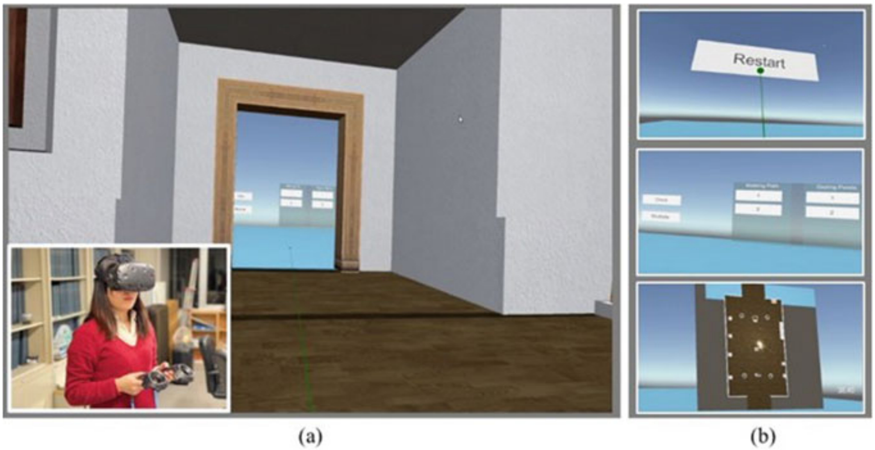


Fig. 2. A participant using **a** the proposed system and **b** its interactive components roaming in an immersive virtual environment.

- Each participant will enter all experimental scenarios in turn, and there is a 5-min break for scene transitions. The order of the experimental scenes was randomized for each participant.
- Letting them roam freely in the experimental scene without their knowledge for a period determined by themselves.
- Letting the participants fill in the questionnaires including their basic demographic information, the simulator sickness, VR-based system evaluation and PANAS scale.

3 Experiments and Results

To showcase this tool, we utilize an exhibition hall of a museum design as an illustrative example. First, we prepared and constructed two contrast indoor light environment design schemes in 3D modeling software and then translated the 3D models into a VR environment with realistic rendering. Next, 10 participants were invited to roam in the spatial schemes and finish a questionnaire of their features and experiences afterward. And meanwhile, this VR system will record participants' positions, head rotations, and timestamps in milliseconds in the game engine. Then, by extracting three types of behavioral data, including travel trajectory, travel time, and gaze points, participants' path, area of interest, and gaze points were mapped of visualization. Finally, combined with participatory feedback from user questionnaires and visualized behavioral results, designers can compare and evaluate different indoor light environment design schemes for optimization.

We designed a virtual model of a museum gallery space 16 m long, 10 m wide, and 6 m high, with a total area of 160 m^2, with dimensions similar to the actual exhibition space. There are 11 virtual booths (with exhibits) in the space. The wall and ceiling materials simulate latex paint and the floor materials simulate a non-glossy wooden floor. The gallery includes a 25 m^2 top skylight and four sets of light fixtures, each consisting of three spotlights. Figure 3 shows the floor and profile of the designed virtual showroom. The artificial lighting is top directed with a color temperature of 3300 K and a color rendering index (cri) of 90. The natural lighting conditions are simulated as the sun's position at 14:00 at the same time of the year (the clear day on December 22) in the same location (Tokyo, Japan). In scenarios A and B, the exhibition halls were designed for artificial lighting, and mixed lighting (artificial lighting together with natural lighting), respectively (Fig. 4).

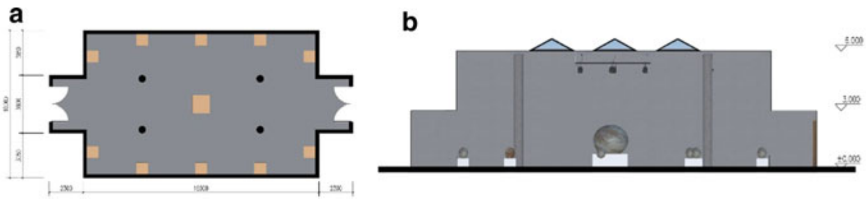
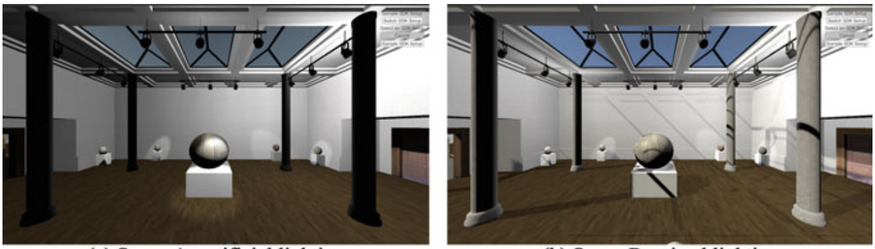


Fig. 3. **a** Floor and **b** section drawings of designed virtual exhibition space.



(a) Scene A: artificial lighting (b) Scene B: mixed lighting

Fig. 4. Lighting scenes in the experimental exhibition hall: **a** scenario A with artificial lighting and **b** scenario B with mixed lighting.

A total of 30 participants (15 female and 15 male) with backgrounds in environmental design participated in this experiment, aged between 20 and 30 years old. Participants were unaware of the experimental scene in advance and were informed of the potential risks that could be present in the experiment.

All the participants completed the questionnaires at the end of each scenario, including their basic demographic information, the simulator sickness, VR-based system evaluation, and the positive and negative affect scale (PANAS). None of the subjects reported any discomfort or were asked to stop the experience. In the evaluation questionnaire for the VR-based system, 90% of the participants reported that the virtual architectural environment was realistic and immersive, while 73.3% reported that the lighting simulation in the virtual scenes was similar to the real scenes and 6.7% felt that the lighting rendering in the virtual scenes was not realistic enough. In addition, 93.3% of the participants found the interaction logic of the controllers in the system easy to understand, while

6.7% of the participants felt that the device took some time to get up to speed. Finally, 26.7%, 63.3%, and 10% of the participants believed that their behaviors performed with the VR system and HMD device in the virtual scene will be consistent, similar, and different, respectively, from those performed in the same scene in the real world.

The results of the PANAS questionnaire revealed that the majority of participants (63.3%) preferred mixed lighting (artificial and natural lighting). It is worth noting that 73.3% of the participants felt that artificial lighting was more conducive to focusing on the exhibit itself, and 86.7% of them felt more active, interested, and inspired in the artificial lighting scenario. In addition, 10.0% of the participants felt slightly nervous in the artificially lit scenes.

Travel trajectories are recorded at a frequency of one route point every 0.2 s. Each participant's route trajectory and travel time are recorded individually. Based on these data, we can analyze the trajectories and travel areas of interest individually or collectively. Figure 5a and b shows the travel trajectories and travel time of a participant in scenarios A and B. Figure 5c and d shows the summary of trajectories of all participants in scenarios A and B. As the dwell time increases, the transparency of participants' trajectory points gradually decreases. The average travel time for all participants in scenarios A and B were 489 and 378 s, respectively.

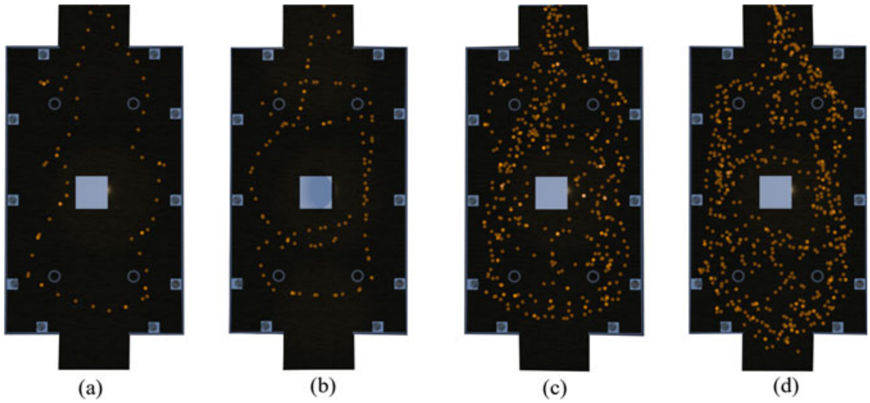


Fig. 5. Travel trajectories example of a participant in **a** scenario A and **b** scenario B and the cumulative trajectories of all participants in **c** scenario A and **d** scenario B.

The collected gaze point data can analyze which objects or information in the virtual environment attract the participants' attention. The frequency of gaze points was recorded once in 0.2 s. To better demonstrate the distribution of gaze points in space, we set up 3 different camera views. Figures 6 and 7 show the gaze points of one participant and the cumulative gaze results of all participants from three perspectives in scenarios A and B. As the dwell time increases, the transparency of participants' gaze points gradually decreases.

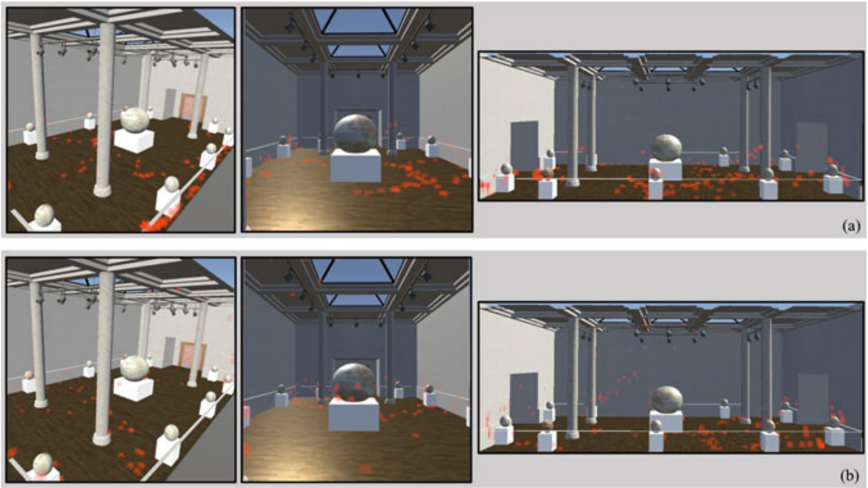


Fig. 6. A gaze points example of a participant from three perspectives in scenario A (**a**) and scenario B (**b**).

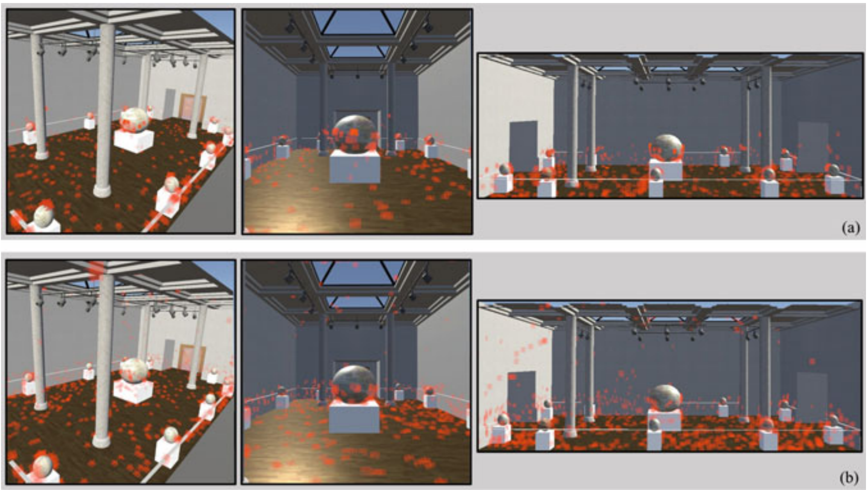


Fig. 7. Cumulative gaze results of all participants from three perspectives in (**a**) scenario A and (**b**) scenario B.

4 Discussion

This study uses the proposed VR system to record behavioral data while participants can walk and watch freely in the 3D space constructed by the game engine, which facilitates the analysis of participants' behavioral patterns under different light environment scenario simulations. Human behavior analysis based on VR technology applied to feedback-based design studies of indoor lighting environments is not common in previous related studies [8]. The results of the participant's questionnaire on VR-based system evaluation showed that the majority of people considered the system to be able to simulate virtual and real scenes and behaviors under the scenes more consistently, while being easy to operate. Therefore, the application of the proposed VR tool to the study of feedback-based interior light environment design is feasible, easy to use, and effective.

The results of the PANAS questionnaire on this and lighting preferences in the physical environment are consistent with previous studies [1]. Therefore, to meet the lighting preferences of users, design teams can provide more opportunities for natural light-harvesting in the experimental virtual environment. The results for the different emotional behaviors exhibited by participants in different light environments suggest that first, for some valuable and time-consuming exhibits, designers can use artificial lighting solutions to provide users with a focused atmosphere. Second, the partially dark light environment in the artificially lit room caused discomfort for a few users. Since to reduce the harm of light on the exhibits, the artificial lighting design guidelines suggest minimizing the illumination of the light source without affecting the normal activities of the occupants.

As shown in Fig. 5c, in the mixed lighting scene, the pedestrian trajectory points are more chaotic and relatively abundant in pedestrian trajectories. In Fig. 5d, in the artificial lighting scene, there are more highlighted stopping points which indicate that the fixed time of a single stopping point is significantly longer than in the mixed lighting scenes. In addition, we can observe some regions of interest, which are regions consisting of a high density of footprint points in Fig. 5c and d. In the artificial lighting scene, many of the regions of interest are near the exhibit in the center of the room, while the distribution of the regions of interest in the hybrid lighting scene is more uniform. These suggest that people in the hybrid lighting scenes prefer motion-based dynamic viewing behaviors, while the artificial lighting scenes tend to focus on stopping behaviors.

As shown in Fig. 7a, the gaze points in the artificial lighting scene were more focused on the exhibits, with almost no gaze points outside the illuminated range of the artificial light. In contrast, in Fig. 7b, the mixed lighting scene had a wider range of gaze points, with gaze points on the ceiling or wall caused by looking up or around. In addition, Fig. 7a has relatively more gaze points with low transparency, which implies that participants in the artificial lighting scene have longer single-point gaze time. Interestingly, the average travel time of all participants in the mixed lighting scenes was 29% higher than in the artificial lighting scenes. This suggests that natural light has a negative impact on participants' gaze duration, but a positive effect on pedestrians' willingness to stay in space.

Taken together, these results suggest that different lighting schemes have an effect on human behavior patterns and that the introduction of natural light usually stimulates more movement. Therefore, architects can design the light environment of the exhibition hall according to the exhibits' viewing characteristics and the desired viewing behavior.

The generic VR system presented in this study provides a systematic approach to collecting user behavioral information and preferences using immersive virtual environments, and such data collected can be used to improve the design of buildings based on user preference feedback. There are still some limitations. First, the proposed VR system makes it difficult to measure and evaluate the group behavior of humans. The current experiment only allows one person to roam in the venue, therefore, the method does not simulate the interactive behaviors, such as avoidance and gathering, that occur in a real environment with multiple people in the same space. Secondly, this experiment was only a control experiment for the lighting method (artificial and mixed lighting). In the complete light environment design, there are several light environment parameters (such as booth illumination uniformity, light color temperature, light source direction, etc.) that have not been further experimentally verified. It is possible to extend other light environment factors to collect user feedback-based behavioral information for designing detailed architectural lighting solutions suitable for users' needs and preferences. Third, the current tracking for the gaze point is based on the result of the center point of the line of sight, ignoring the situation of the gaze point shift due to the possible eye rotation in practice. Finally, the proposed VR system has only been experimented on fully virtual scenarios to verify its feasibility. In the future, controlled experiments with real sites and realistic rendered virtual scenes should be introduced to better evaluate the effectiveness of this VR system.

5 Conclusion

This paper presents a generic tool for collecting user behavior information (including travel trajectories, travel times, and gaze points) in an immersed indoor light environment based on virtual reality technology. By capturing and analyzing this information and user feedback, designers can translate this information into design boundaries promptly to ensure human-centered indoor light design. To demonstrate how to use our proposed VR system for feedback-based design in the schematic phase of a building, we showed an experiment in which we collected and analyzed behavioral data from 30 participants in artificial and mixed-light environments. The results showed that the VR system can collect and analyze human behavior data of walking, staying, and watching, and showed participants were willing to stay longer in the space under mixed lighting. The results of this study can help architects get timely feedback from users so that they can create spaces focused on the needs and preferences of end-users and improve user satisfaction, rather than just designing according to laws and codes. In future research, we will introduce eye-tracking as well as controlled experiments on real sites to further develop and validate the proposed VR tool.

References

1. Ai X, Wu Z, Guo T, Zhong J, Hu N, Fu C (2021) The effect of visual attention on stereoscopic lighting of museum ceramic exhibits: a virtual environment mixed with eye-tracking. Informatica 45. 10/gnhs8r
2. Chen H, Hou L, Zhang G, (Kevin) Moon S (2021) Development of BIM, IoT and AR/VR technologies for fire safety and upskilling. Autom Constr 125:103631. 10/gjn6jv
3. Feng Y, Duives DC, Hoogendoorn SP (2021) Using virtual reality to study pedestrian exit choice behaviour during evacuations. Safety Sci 137:105158. 10/gh4vjn

4. Heydarian A, Pantazis E, Wang A, Gerber D, Becerik-Gerber B (2017) Towards user centered building design: Identifying end-user lighting preferences via immersive virtual environments. Autom Constr 81:56–66. 10/gbpcn5
5. Li Y, Yabuki N, Fukuda T (2022) Exploring the association between street built environment and street vitality using deep learning methods. Sustain Cities Soc 79:103656. 10/gn6gmp
6. Li Y, Yabuki N, Fukuda T, Zhang J (2020) A big data evaluation of urban street walkability using deep learning and environmental sensors-a case study around Osaka University Suita campus. Presented at the proceedings of the 38th eCAADe conference, TU Berlin, Berlin, Germany, pp 319–328
7. Lin J, Cao L, Li N (2020) How the completeness of spatial knowledge influences the evacuation behavior of passengers in metro stations: a VR-based experimental study. Autom Constr 113:103136. 10/gnbnh3
8. Xiao H, Cai H, Li X (2021) Non-visual effects of indoor light environment on humans: a review☆. Physiol Behav 228:113195. 10/ghjp3v
9. Yan M, Tamke M (2021) Augmented reality for experience-centered spatial design—a quantitative assessment method for architectural space. Presented at the Towards a new, configurable architecture, Proceedings of the 39th eCAADe conference-Volume 1, Novi Sad, Serbia, pp 173–180
10. Zhang J, Fukuda T, Yabuki N (2021) Automatic object removal with obstructed façades completion using semantic segmentation and generative adversarial Inpainting. IEEE Access 9:117486–117495. 10/gm6hpm

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