Generative AI-Augmented Decision-Making for Elderly Seating Comfort in Community Micro-Spaces

A VR-based design approach

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Based on the increasing global aging population, the demand for age-friendly renovation of urban micro-spaces is growing, particularly in the design of seating preferences for the elderly in public areas. However, traditional age-friendly renovations often face issues such as delayed and vague design evaluations, as well as difficulties in capturing the elderly's needs. This study proposes an interactive design framework through the collaborative work of generative AI, Grasshopper, and VR, which can dynamically generate optimized seating space designs based on elderly users' preferences and spatial environments in real-time. VR experiments were conducted using 3D scanned site models, with two experimental groups focused on "seating space selection" and "seating view preferences" to comprehensively optimize seating comfort. By combining a pairwise comparison preference test, the design elements are dynamically adjusted, establishing preference ranges for both facility and environmental factors for the elderly, thus addressing the time-space delay issues in traditional design evaluations. Additionally, the study introduces a lightweight approach that uses Stable Diffusion to generate high-precision 2D images in real time, which are integrated with pre-scanned 3D models. This reduces the rendering burden of VR scenes and improves system responsiveness and operational fluency. A comprehensive focus group evaluation shows that the system effectively bridges the communication gap between elderly users and designers, improving the accuracy and efficiency of design decisions and increasing public participation in renovation design. However, some limitations still exist. This approach offers an efficient, personalized, and scalable intelligent design framework for future age-friendly renovation of community micro-spaces.

Keywords: *Aging-Inclusive Design, Virtual Reality, AI-Generated Content, Design Decision, Real-time Feedback, Elderly Seating Preferences, Pocket Parks.*

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INTRODUCTION

Community micro-spaces (Micro Public Spaces) refer to small-scale, functionally flexible public spaces within urban neighborhoods. They are small urban public spaces focused on daily life. As global aging continues to accelerate, the importance of micro-scale external spaces within communities grows, especially in terms of meeting the resting needs of

elderly people (Akinci et al., 2021), improving psychological comfort, and fostering social interaction (Liljegren et al., 2024). Sitting activities are common and frequent behaviors for the elderly in community public spaces (Sun et al., 2020), with both their frequency and duration increasing significantly as people age. However, current research tends to focus on the overall quality of community spaces, with little systematic exploration of aging-friendly renovations for micro-spaces dedicated to sitting (Luo et al., 2022). Additionally, traditional approaches to space renovation and evaluation are often slow and ambiguous (Chen, Bowring and Davis, 2023). They lack effective and rapid feedback mechanisms, which makes it difficult to identify and implement specific design changes quickly, resulting in inefficient design updates. Furthermore, due to limited design knowledge and physical constraints, elderly individuals struggle to clearly express their spatial preferences through traditional surveys, leading to low levels of participation (Ng et al., 2024). This "cognitive gap" between designers and users makes it challenging for existing renovation designs to accurately reflect the needs of the elderly, highlighting the urgent need for an intelligent decision support system that can capture these needs in real-time and generate quick feedback.

Advantages of AIGC in architectural assessment and renovation

AIGC (Artificial Intelligence Generated Content) represents a novel approach to the generation of architectural renderings and spatial imagery through artificial intelligence, building on the trends of professional-generated content (PGC) and user-generated content (UGC). The advancement of AIGC technology presents revolutionary opportunities for architectural renovation and evaluation. Wen et al. (2023) examined AI-facilitated group brainstorming, highlighting the role of artificial intelligence in design collaboration, which enhances idea generation and team interaction. Doumpioti and Huang (2023) proposed a process for generating images from text prompts and converting them into structured environmental data, offering a more scientific approach to architectural design. Huang (2024) explored a personalized interior design method based on MBTI (Myers-Briggs Type Indicator) personality types, using generative artificial intelligence to deliver tailored spatial designs for users with varying personality traits. Mugita, Fukuda and Yabuki, (2023) applied diffusion models and instance segmentation technologies for visualizing future landscapes, generating intuitive renderings of renovated landscapes that enable all stakeholders to actively participate in the design process and visually express their proposed future landscapes.

These studies illustrate the advantages of using generative artificial intelligence models: 1. The ability to create personalized and customized design solutions based on client preferences and needs. By analyzing client preferences, lifestyles, and spatial requirements, the model can offer design proposals that align with individual specifications. 2. The use of lightweight image generation technologies, which provide quick and intuitive renderings of renovation proposals. This technology makes it easier for non-design professionals to understand and contribute to design decisions, fostering a shared vision for the project and potentially reducing rendering load in VR environments. These studies collectively highlight how generative AI can enhance participatory design, especially by translating subjective preferences—such as those from elderly users—into concrete design outputs with minimal cognitive burden.

Advantages of VR in Architectural Assessment and Renovation

Virtual reality (VR) technology provides distinct advantages not only in immersion but also in enabling rapid, binary comparison of design options with synchronized user input. While static renderings can visualize fixed scenes, VR allows participants to intuitively pan their view, experience spatial transitions, and receive immediate visual feedback based on their preferences. This dynamic

adaptability is particularly important in aging-inclusive design contexts. Through immersive virtual environments, users can experience various design options, enhancing their intuitive understanding of the space and fostering emotional connections with the design (Ghadirian and Bishop, 2008). Furthermore, VR plays a crucial role in improving spatial awareness, helping users visualize spaces accurately and increasing their sensitivity to the spatial impacts of design decisions (Arthur, 2003). VR's ability to simulate pre-construction allows designers to refine their proposals in real-time during the conceptual phase, moving away from the traditional, linear feedback model. This iterative process creates a "perceive-generate-validate" loop, fostering more dynamic and effective design evaluations (Li, Sun and Zou, 2023). However, current VR applications still face challenges in handling the large data volume of 3D models, which places a significant rendering load on the system and limits the speed of iterations (Selzer, Larrea and Castro, 2022; Li, Sun and Zou, 2023).

Though a single rendered image or panorama might seem enough in a static setting, VR offers more than immersive views. It supports embodied spatial judgment, crucial for elderly users with limited abstract reasoning. Even seated, users naturally move their heads to perceive subtle differences in openness, shading, and enclosure—key comfort factors hard to judge from static images. Our study's binary preference testing requires real-time visual updates from user input, which static images can't provide. This interactive process lets users refine their design choices gradually, making VR a dynamic platform for expressing preferences and guiding adaptive design.

Research Objectives

This study aims to address the dual challenges of feedback delays and limitations in user expression within the design of aging-friendly seating for urban micro-spaces. The research is centered around two main objectives: First, to develop a real-time design feedback system based on AIGC, utilizing a lightweight LoRA model to provide real-time, high-precision 2D rendering textures for VR scenes. This system will dynamically generate seating designs that align with user preferences and local styles, overcoming the time and spatial delays typically found in the traditional design process's "evaluation-adjustment" phase. Second, to create an immersive, VR-driven interactive decision-making framework. By employing binary preference testing and eye-tracking technology, the framework will convert elderly users' implicit perceptions of seating materials and forms into quantifiable design parameters. These parameters will then directly influence the optimization of the AIGC generator's constraints. This system will offer a highly efficient and scalable feedback mechanism, providing a quantifiable decision-support tool for aging-friendly renovations in high-density urban renewal projects.

METHODOLOGY

The experiment follows the research-driven design framework developed by Xu Lei-qing and colleagues. First, a lightweight real-time optimization mechanism combining 3D scanning, VR experience, and generative AI will be established to assist users in making preference-based decisions (Figure 1). Second, the effectiveness of the design method will be assessed using focus group ratings and interviews (Zheng et al., 2024).

3D Scanning for VR Experiments

The 3D scanning model enhances real-time experiences in VR, improving the convenience of experimental feedback and enabling users to explore different perspectives (Zhu, Lin and Li, 2022). Using VR technology to study elderly behavior and aging-friendly space renovations is both feasible and convenient. It allows researchers to examine typical solutions that are hard to access in real life and facilitates the comparison of multiple renovation options simultaneously. Moreover, VR technology enables quick modifications to environmental features, thus improving research efficiency (Qi, Lu and Chen, 2022).

To optimize seating comfort in a space, a 3D scan is first conducted to create a site model. The scanning process uses Scaniverse software, which can be installed on a mobile phone. This software allows for easy and portable 3D scanning by simply capturing video footage of the space to be renovated. The scanned models are then exported in FBX format, allowing them to be linked with VR devices for immersive experiments.

Paired comparison method

In the experiment, the paired comparison method was employed to assess and compare the impact of different design elements or spatial characteristics on user preferences. By directly contrasting two design options or alternatives, and progressively narrowing down the comparison scope, users are able to more clearly articulate their preferences, helping researchers or designers make more informed and precise design decisions (Figure 2).

Based on a review and synthesis of existing literature, this paper identifies two main categories of design variables used in paired comparisons, specifically those influencing the seating comfort of the elderly: facility elements and environmental elements. Facility elements include the color, shape, material, and layout of the seating, which directly affect the seating behavior of elderly individuals. Environmental elements, on the other hand, include factors such as the level of shelter provided by the seating, the openness of the view, the depth of the foreground, the degree of enclosure, and the diversity of plant species. These factors reflect elderly individuals' preferences for seating environments and also indirectly affect their seating behavior.

Together, facility and environmental elements form the variable categories in this study, which directly inform the specific modifications to the design elements. By comparing these variables through paired comparisons, researchers can not only observe the effects of different design solutions on elderly seating behavior but also dynamically adjust the design options based on research needs, thereby enhancing both the efficiency and practical value of the study.

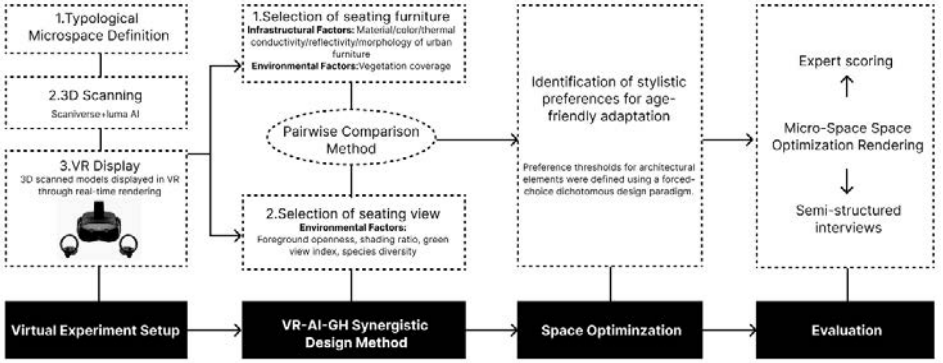
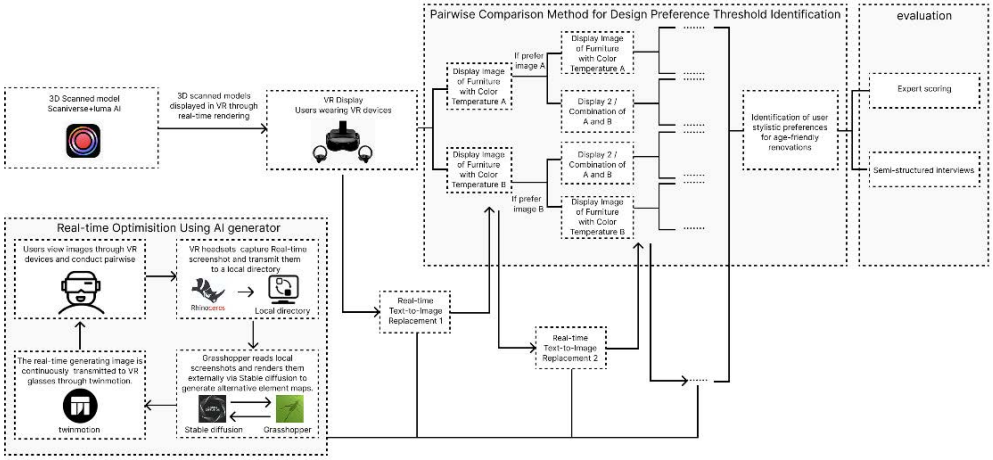


Figure 1
Experimental workflow

Figure 2
Feedback mechanism workflow



AI-Generated Feedback Loop

The limitations of VR system hardware and software often force experimental designers to find a balance between image realism and the smoothness of dynamic images. Under the same conditions, the more detailed and realistic the image, the more it impacts image smoothness, both of which influence the dynamic realism of the virtual experiment (Li, Sun and Lin, 2022). High rendering demands have become a key limitation for the use of VR systems in architecture.

To address the rendering load caused by large-scale 3D model data, this study developed a lightweight, real-time optimization feedback mechanism that integrates 3D scanning, VR interaction, and generative AI. A key innovation lies in the deployment of a LoRA-optimized Stable Diffusion model, which significantly reduces the computational demand while preserving visual fidelity. On an RTX 3080Ti GPU, each frame is generated in approximately 1.2 seconds, enabling quasi-real-time response suitable for participatory design workflows. Technically, real-time screenshots of the participant's field of view in the VR device are taken and stored locally. Grasshopper continuously monitors local screenshot directories and triggers the generation of updated textures via Stable Diffusion. These are then integrated into the VR environment through Twinmotion, ensuring a stable framerate and minimal latency. To ensure consistency across AI-generated scenes, we adopted a masked-prompt strategy in Stable Diffusion, which allows localized modification of specific design elements while maintaining the overall spatial context. By utilizing generative AI to create real-time 2D element renderings from the participant's viewpoint, this method replaces the real-time generation and rendering of 3D models, thus reducing the VR scene's rendering load. This approach, combining high-precision 2D images with a simplified base model, supports smoother real-time rendering and optimization.

This AI-based feedback mechanism effectively balances visual detail and dynamic smoothness in virtual reality by optimizing the real-time rendering process. By reducing the rendering burden on VR systems, it improves system efficiency and provides a more effective tool for virtual design evaluation in architecture. This mechanism holds promise for broader applications of VR in architectural design.

Figure 3
VR interface and participant testing

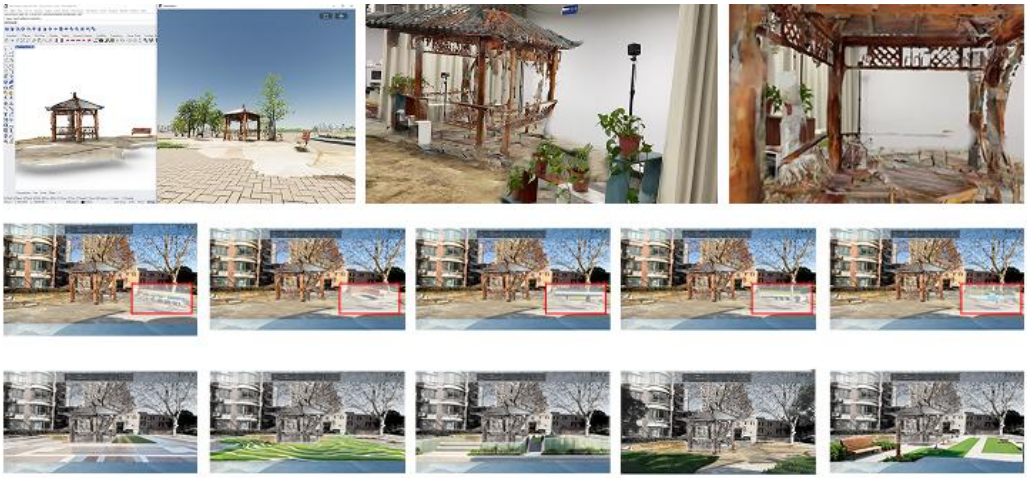


Figure 4
SD-generated textures in VR environment

Evaluation mechanism

We use the focus group method for evaluation, as it effectively gathers subjective opinions from participants and uncovers design issues through group discussions. Zheng et al. (2024) emphasized that the focus group method can effectively capture user feedback in virtual reality environments; Bollo and Collins (2017) indicated that this method helps designers understand users' actual needs; Scott (2017) found that the method promotes effective interaction between designers and elderly users in space design; Lu et al. (2011) further verified its effectiveness in elderly environment research. Therefore, the focus group method is applied in this study to evaluate the design approach that integrates AI and VR, ensuring the optimization of elderly seating comfort. We formed a focus group to assess the effectiveness of this design approach, conducting systematic evaluations of the generative AI-enhanced VR design system's effectiveness in improving elderly seating comfort
through quantitative questionnaires and qualitative interviews.

In the Likert scale questionnaire, participants were asked to rate the design method on a scale from 1 to 5, based on four key criteria: (1.) Environmental Perception Validity, referring to how accurately and immersively the VR scene replicates real-world space features; (2.) Interaction Usability, assessing the smoothness and clarity of the binary choice process; (3.) Design Adaptability, measuring how well the AI-generated solutions align with the needs for aging-friendly seating space renovation; and (4.) Technology Acceptance, evaluating the potential for the future adoption of the VR-AI integrated design method.

In semi-structured interviews, participants were asked to discuss two open-ended questions: their attitudes and suggestions regarding VR and generative AI technologies, and their recommendations for improving the evaluation method for seating space optimization.

EXPERIMENT

The participants in this experiment include elderly individuals, designers, and other stakeholders from the area to be renovated. They interacted with 3D models in a VR scene and made selections to identify their preferences (Figure 3).

The experimental process consisted of two main tasks designed to address both the location and environmental quality of seating in urban micro-spaces. First, in the seating space selection task, participants, in standing position, evaluated whether they would choose to sit in a given seat placed at a specific location in the VR environment—this directly exploreed spatial placement factors such as shading, openness, and proximity. Second, in the seating landscape preference task, participants (now seated) assessed their satisfaction with the surrounding design elements from a fixed seated viewpoint.

The experiment used a binary preference test, where a single variable was controlled at a time. By adjusting the parameters of a facility or environmental factor (Factor A), multiple virtual scenes were created, and participants experienced and selected whether they were "satisfied" or "dissatisfied." The binary method gradually narrowed the range of the variable, converging to the optimal preference range [An, Am] for Factor A. This concluded that group of experiments. After all participants completed the preference testing for the variables needing adjustment, the results produced customized, region-specific, and stylized preferences and updated renderings for aging-friendly seating space renovations.

RESULTS AND DISCUSSION

The hardware and software limitations of VR systems often force experimental designers to seek a balance between image realism and dynamic image smoothness. The VR-assisted design and binary communication system developed in this study prioritizes interaction

fluidity while maintaining reasonable environmental fidelity.

This study selected four elderly participants with diverse backgrounds (a 70-year-old community resident, a 70-year-old retired engineer, a 75-year-old person with limited mobility, and a 68-year-old socially active individual) as samples to conduct a multi-dimensional evaluation of the VR-assisted design communication system. The assessment framework focused on four core dimensions: environmental perception validity, interaction usability, design adaptability, and technology acceptance, aiming to examine the system's performance and practical value.

Questionnaire and Structured Interview Results Analysis

The quantitative evaluation results (on a 5-point scale) reflected performance differences across dimensions: environmental perception validity scored 4.0, indicating that VR technology achieved high realism in spatial environment simulation; interaction usability received 3.38, the lowest among the four dimensions, revealing significant barriers in operational convenience; design adaptability scored highest at 4.63, confirming the excellence of AI-assisted design in identifying and meeting specific needs; technology acceptance was 3.5, reflecting participants' cautiously optimistic attitude toward this new technology. Significant differences existed in evaluations from participants with varying backgrounds: the retired engineer with technical background rated the system highest (average 4.38), while the participant with mobility limitations gave the lowest rating (average 3.25). This difference revealed the system's deficiencies in accessibility design while highlighting how users' technological literacy impacts VR technology acceptance.

Semi-structured interviews provided deeper insights. Participants generally recognized VR technology's advantages in spatial design visualization but expressed concerns about operational complexity and user comfort. Key challenges included: (1.) technical usage barriers, such as VR-induced dizziness and operational complexity; (2.) lack of accessibility design, particularly for users with mobility limitations; (3.) limited social interaction features, making it difficult to support collaborative decision-making.

Interview results pointed to three improvement directions: simplifying the interaction interface, enhancing multi-user collaboration capabilities, and strengthening accessibility design. Participant E3 (with mobility limitations) emphasized: "The system should consider the special needs of wheelchair users," highlighting the importance of inclusive design.

Limitations and Future Work

One limitation of this study is the impact of VR immersion on experimental results. The 3D scanning models used in this VR environment have relatively low resolution, which may affect the participants' sense of immersion and, in turn, interfere with the experimental outcomes. Although some studies have confirmed the effectiveness of VR simulation technology in specific scenarios, a general consensus has yet to be reached.

Another limitation is the insufficient consideration of multiple stakeholders. The users of community micro-spaces include all residents, not just elderly individuals, but also young people and children. Balancing the behavioral needs of these different groups is an important issue in urban renewal.

It is important to acknowledge that the current framework focuses primarily on visual comfort, leveraging accessible visual proxies to accommodate the cognitive needs of elderly participants. However, this approach does not yet capture key non-visual dimensions such as thermal, tactile, and acoustic comfort. Additionally, the study has not fully addressed the role of spatial dynamics—specifically, how the presence and movement of others in shared environments influence seating behavior. These sensory and social dimensions represent important directions for future research to achieve a more holistic

understanding of age-friendly spatial experience. Finally, the sample size used in this experiment was limited to a controlled laboratory setting. Future work could involve developing a web-based VR testing platform to enhance the participation of various stakeholders in community renovation projects. With an expanded sample size, it would be possible to build an AI-driven, aging-friendly seating space stylized semantic database, which would serve as an effective tool for researching and evaluating aging-friendly renovations.

CONCLUSION

This study integrates VR technology with AIGC to propose an innovative framework for aging-friendly renovation of community seating spaces. The method shows clear advantages in optimizing the design process, increasing design decision efficiency, and addressing the personalized needs of elderly users. By offering quick feedback and customizing preference settings, the study enables rapid assessments and tailored designs based on elderly needs, improving the usability and practicality of spatial solutions. The introduction of the lightweight LoRA model allows for customized design styles. Additionally, the binary method bridges the communication gap between elderly users and designers, facilitating precise needs expression and feedback. This not only enhances user participation in renovation projects but also improves the flexibility and efficiency of design decisions.

Technically, the use of real-time 2D texture generation replaces traditional 3D rendering, reducing the computational load of virtual scenes, enhancing system response speed, and improving usability. This study proposes not just a toolchain integration, but a closed-loop design feedback framework that captures elderly users' implicit preferences through binary comparison and translates them into real-time generative constraints. This protocol bridges the cognitive gap between users and designers, offering a replicable and scalable participatory model for aging-inclusive micro-space design. Future studies can expand this approach to diverse environments while integrating multi-sensory feedback—such as thermal comfort, material textures, and ambient sound—into the VR system to enable more comprehensive, aging-friendly comfort evaluations beyond visual perception.

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