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Research of Young Adults' Residential Floor Plan Preferences Through 2D Visualization and Immersive Virtual Environments: A Comparison with Quantitative Floor Plan Attributes

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Abstract

This study investigates young adults' residential floor plan preferences through the Traditional 2D environment and immersive virtual environments and explores whether immersive virtual environments can more effectively identify young users' expressed preferences under simulated pre-occupancy evaluation conditions. It further examines the relationship between subjective preferences and quantitative floor plan attributes. Eight small and medium-sized apartment units currently on the market in Fukuoka, Japan, were selected as case samples. First, a quantitative evaluation framework was established by combining space syntax analysis and principal component analysis, through which floor plan attributes were reduced to three interpretable dimensions: privacy, comfort, and functionality. Second, a within-subject experiment was conducted in which 20 young participants evaluated the same eight floor plans under both 2D and immersive virtual reality conditions using the Residential Spatial Satisfaction Questionnaire. The results show that the virtual reality condition produced significantly higher ratings for privacy, comfort, functionality, and overall satisfaction than the 2D condition. In addition, immersive virtual reality yielded greater plan discriminability and clearer group-level preference rankings, indicating that it more effectively reveals differences among alternative housing schemes. However, the preference rankings derived from subjective evaluation in virtual reality showed only limited agreement with the rankings generated by the principal component analysis-based physical framework, suggesting that objectively optimized spatial attributes do not automatically correspond to users' expressed residential floor plan preferences. Overall, the findings indicate that current housing design logic may not fully respond to the experiential needs of potential young users, and that early-stage residential design evaluation should place greater emphasis on user-centered assessment. Compared with traditional 2D representation, immersive virtual reality provides a more effective medium for pre-occupancy housing evaluation and preference-based design decision making.

Keywords: residential floor plan evaluation; immersive virtual environment; traditional 2D presentation; housing preference assessment; principal component analysis; residential spatial satisfaction questionnaire

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1. Introduction

Housing has consistently been one of the research subjects in the architecture, engineering, and construction (AEC) industry that is closest to everyday life, while also being among the most difficult to evaluate [1,2]. With ongoing social development, demographic change, and the continuous transformation of lifestyles, residential needs no longer correspond in a stable manner to the conventional logic of housing provision. Particularly for contemporary younger generations, housing is not merely a physical space that accommodates basic living functions, but also a setting that carries multiple expectations related to comfort, privacy, and personalized use. Existing studies have shown that residential satisfaction is closely associated with factors such as dwelling size, level of privacy, spatial organization, and lifestyle, while different user groups also demonstrate significant differences in their judgments regarding the importance of these housing attributes [3–5]. This suggests that spatial organization strategies in conventional housing design, which are typically shaped by experience and generalized standards, may not accurately respond to the actual needs of end users.

At present, existing housing research is largely based on post-occupancy satisfaction surveys, preference questionnaires on housing attributes, or market-based statistics, with the primary aim of identifying which housing attributes users value. However, insufficient attention has been paid to user preferences regarding unbuilt design proposals at the design stage [6]. This issue is particularly critical in residential design practice. In the early phase of design proposal development, potential users are often not adequately incorporated into design decision-making. As a result, designers are required to anticipate the needs and spatial use patterns of future residents under conditions of incomplete information, while users themselves often find it difficult to form concrete spatial judgments based solely on drawings or abstract descriptions [7,8]. Consequently, the formation of residential design proposals can easily rest on an insufficient cognitive basis, thereby increasing the risk that the final design outcome will deviate from actual user needs.

Meanwhile, driven by the Fourth Industrial Revolution and the digital transformation of the AEC industry, architectural design is gradually shifting from a traditional model dominated by drawing-based representation and experience-based judgment toward a decision-making approach that integrates digital simulation, immersive perception, and early-stage validation [9–11]. Against this background, virtual reality (VR) has provided a new methodological foundation for architectural design evaluation. Existing studies have noted that the application of VR in architecture has expanded from early-stage visual presentation to broader areas such as design review, user participation, and support for user-centered design [1]. Compared with traditional two-dimensional (2D) plans, renderings, and screen-based three-dimensional displays, immersive virtual environments can convey unbuilt architecture and its spatial details more comprehensively, while also enhancing users' understanding of future use scenarios through active exploration [12]. Related studies have further shown that, compared with 2D approaches, immersive environments are more effective in supporting spatial understanding, emotional evaluation, and preference judgment [1,7,12].

Despite these advances, a clear disconnect remains across existing studies. On the one hand, research on residential satisfaction has provided relatively sufficient insight into the housing attributes that users care about, yet it has paid limited attention to the direct identification of potential users' preferences at the design stage [2]. On the other hand, although virtual reality research has demonstrated that immersive environments are beneficial for spatial understanding and design review [13], there is still a lack of direct evidence, particularly in the context of residential design and in direct comparison with traditional 2D representations, as to whether such environments can produce clearer and

more reliable preference identification outcomes. In addition, although existing studies on residential floor plans have begun to incorporate spatial attributes into quantitative analytical frameworks, it remains to be further examined whether subjective preferences formed under different presentation media can establish stable correspondences with the quantifiable attributes of residential floor plans.

Based on this, this study focuses on preference identification at the unbuilt residential design stage and targets contemporary young users. It compares the differences between traditional 2D representations and immersive virtual environments in residential evaluation and preference judgment and further examines the relationship between subjective preferences and the quantifiable attributes of residential floor plans. In doing so, it aims to provide methodological support for shifting residential design from experience-based judgment to experience-informed validation, and from standardized supply toward more user-responsive design support.

2. Literature Review and Research Questions

2.1. Young Adults' Residential Satisfaction and Housing Preference Formation

Residential satisfaction is generally regarded as a multidimensional evaluation shaped by the combined effects of housing attributes, residents' socioeconomic conditions, lifestyle, and the surrounding environment [3,14]. Recent studies on apartment housing have shown that design attributes at the residential-unit level are closely associated with residential satisfaction, including interior space, daylighting, natural ventilation, acoustic privacy, visual privacy, spatial layout, and building safety [4,5]. This suggests that residential satisfaction is not determined solely by demographic factors, but is directly related to the internal quality and spatial organization of the dwelling [15].

Housing preferences are likewise influenced by life stage, prior residential experience, and everyday spatial needs. Opit et al. indicated that the housing preferences of young adults aged 25–35 are jointly shaped by residential experience, lifestyle expectations, transportation choices, and constraints in the housing market [16]. At the residential-unit level, these preferences are mainly reflected in concerns regarding room size, layout flexibility, privacy, storage space, daylighting, ventilation, and comfort. Berto et al. further demonstrated that young people are highly sensitive to indoor comfort and are willing to pay additional costs for improved spatial comfort [17]. Therefore, the housing preferences of young adults should be understood as dynamic judgments formed through the interaction of spatial needs, environmental quality, life-stage transitions, and market opportunities.

However, existing studies have largely relied on housing choice surveys, market statistics, post-occupancy evaluations, or satisfaction questionnaires, which primarily explain residents' evaluative outcomes after they have completed housing choices or accumulated residential experience. Such methods remain limited in supporting the early stages of housing design, during which floor-plan organization, room configuration, circulation routes, privacy hierarchy, and functional zoning still allow considerable room for adjustment. Therefore, research on young adults' housing preferences needs to move beyond post-occupancy satisfaction and market choice analysis toward the early evaluation of unbuilt residential design schemes.

2.2. Immersive Virtual Environments in Early-Stage Architectural Design Evaluation

Identifying housing preferences at the design stage first requires addressing how potential users evaluate unbuilt residential spaces. Conventional architectural schemes are typically presented through two-dimensional drawings, renderings, physical models, or screen-based three-dimensional visualizations. These media are useful for professional design communication; however, for non-expert users, they may not adequately support

specific judgments regarding spatial scale, privacy, circulation routes, daylighting, and functional usability [7,18]. This issue is particularly salient in residential design because the evaluation of housing often depends on everyday embodied residential experience rather than merely abstract geometric information.

With the digital transformation of the AEC industry, immersive virtual environments have been increasingly applied to architectural visualization and design review. Previous studies have shown that augmented reality (AR)/VR technologies have considerable potential for design collaboration, communication, and visualization [10], and can further extend the value of BIM by improving collaboration across the design, construction, operation, and maintenance stages [9]. In addition, VR can support immersive exploration of early-stage architectural models, making human-scale relationships and spatial experience more intuitive [19]. Therefore, VR is not merely a visualization tool, but also an effective medium for supporting spatial understanding, design communication, and early-stage validation.

Recent studies have further examined the value of VR from the perspectives of end users and residential clients. Ma et al. found that, compared with conventional 2D visualization, immersive VR can improve the accuracy of users' affective evaluations related to spatial scale and enhance their preference judgments regarding specific design attributes [7]. In the field of residential architecture, BIM-based VR walkthroughs have also been shown to help future users understand room size, door and window positions, furniture arrangement, and spatial relationships, thereby supporting design decision-making and reducing later-stage modifications [20]. However, whether VR is more effective than conventional 2D representation in identifying housing preferences, particularly whether it affects residential satisfaction scores and the discriminability of residential floor plans, still requires further validation.

2.3. Subjective Residential Preference and Quantitative Floor Plan Attributes

The evaluation of residential floor plans is shifting from experience-based judgment toward quantitative and user-oriented assessment. Wang and Duan proposed a generative design framework for multi-unit residential floor plans that integrates consumer satisfaction with energy performance, using indicators such as privacy, comfort, practicality, and convenience for evaluation [21]. Gao et al. investigated the preferences of different household groups for medium-sized apartment floor plans through a questionnaire survey and found that privacy, orientation, storage space, and the number of rooms were important evaluation criteria, with significant preference differences among household groups [22]. These studies indicate that residential floor plans can be evaluated through measurable spatial attributes, although the evaluation results remain influenced by user characteristics and household types.

Meanwhile, statistical methods and spatial configuration analysis also provide a methodological basis for residential evaluation. Principal component analysis (PCA) can be used to extract latent dimensions from complex variables related to residential environmental preferences [23,24], while space syntax enables the analysis of residential privacy from the perspectives of spatial depth, visibility, and spatial configuration [25]. These methods provide support for constructing a quantitative evaluation framework based on multiple residential attributes.

However, the quantitative attributes of residential floor plans do not necessarily correspond directly to users' subjective preferences. Young users' housing preferences are influenced not only by the physical attributes of dwellings, but also by residential experience, lifestyle expectations, transportation choices, and market constraints [16]. In addition, different modes of media presentation may also alter users' preference judgments regarding apartments [26]. Therefore, it is necessary to further compare whether the

ranking of residential floor plans derived from objective physical attributes is consistent with the preference ranking obtained from users' subjective evaluations.

2.4. Research Gap and Research Questions

In summary, existing studies have laid a foundation for research on residential satisfaction, housing preferences, immersive design evaluation, and the quantitative assessment of residential floor plans. However, three limitations remain. First, studies on residential satisfaction and housing preferences have largely been based on post-occupancy evaluations, housing choice surveys, or satisfaction questionnaires, offering limited explanations of how potential users evaluate unbuilt residential schemes at the design stage. Second, VR-related studies have demonstrated the potential of immersive virtual environments for spatial understanding and design communication; however, their specific role in identifying housing preferences, particularly their advantages over conventional 2D representation, remains insufficiently validated. Third, although previous studies on residential floor plans have established quantitative evaluation frameworks, whether the ranking of residential floor plans derived from quantifiable physical attributes is consistent with users' subjective preference rankings still requires further examination.

To address these research gaps, this study compares young potential users' evaluations of eight residential floor-plan schemes in a Traditional 2D environment and an immersive virtual environment. Residential satisfaction is measured using the RSSQ and assessed across three dimensions: privacy, comfort, and functionality. The study examines whether different representational media affect satisfaction scores and housing preference identification. It further compares users' subjective preference rankings with a PCA-based physical framework constructed from quantifiable floor-plan attributes to assess the consistency between the two. Accordingly, this study proposes the following research questions:

RQ1: Are there significant differences in the three-dimensional scores and total scores of the RSSQ between the Traditional 2D environment and the immersive virtual environment?

RQ2: Does the immersive virtual environment demonstrate greater discriminability among floor plans and a more credible preference ranking than the Traditional 2D environment?

RQ3: To what extent is the floor plan preference ranking derived from subjective evaluations consistent with the scores of the physical framework established through PCA?

3. Methodology

This study adopts a methodological framework that combines quantitative analysis of residential floor plans with user experience evaluation, with the aim of exploring how different media influence young users' preference identification in housing assessment and further examining the relationship between subjective preferences and the quantifiable attributes of residential floor plans. Unlike studies that rely solely on post-occupancy satisfaction surveys or single-source subjective evaluations, this study integrates spatial attribute analysis in residential design with user perception experiments conducted at the design stage, thereby establishing a link between subjective judgment and objective attributes within the evaluative context of unbuilt housing.

Specifically, the methodological framework of this study consists of two interrelated dimensions. The first involves the evaluation and quantification of the spatial attributes of the sample residential design proposals based on their floor plans, thereby constructing an objective basis for comparison among the proposals. The second consists of user experience and evaluation experiments conducted across different presentation media, through which questionnaire data were collected to capture young users' subjective feedback on residential space, functional organization, and overall experience. On this basis, the study further

compares the differences between traditional 2D environments and immersive virtual environments in preference identification and examines the consistency between subjective preference outcomes and the quantified attributes of residential floor plans.

Through the above approach, this study attempts to establish a housing evaluation pathway that integrates spatial attribute analysis with user experience feedback, as illustrated in Figure 1, thereby providing a methodological basis for the early-stage evaluation of unbuilt residential design proposals and for more user-responsive design support. The specific procedures for sample selection, floor plan quantification, experimental design, and data processing will be presented in the following sections.

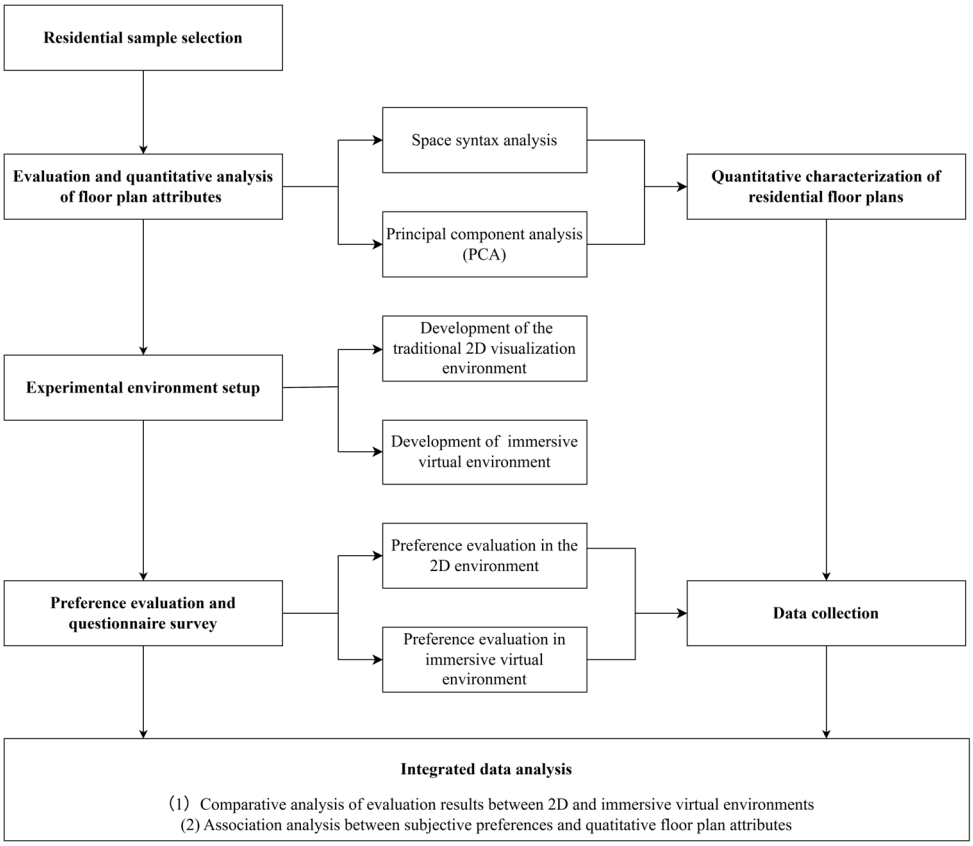


Figure 1. Methodological framework of the study.

3.1. Experimental Data Collection

3.1.1. Selection of Residential Samples and Data Collection

In housing market research, scholars generally agree that consumers' housing preferences are closely associated with specific housing attributes [21]. Some studies have further indicated that demographic factors, such as income, age, marital status, and household structure, have a substantial influence on consumers' preferences for residential attributes [27]. In this context, the present study focuses on the preferences of young single consumers regarding housing attributes. It uses floor plans of unbuilt residential units marketed at the design stage as research samples, while furniture and other spatial elements were arranged and modeled in accordance with the floor plans and renderings provided for these housing units.

In recent years, the Japanese housing market has undergone significant structural changes. As an important group of potential consumers in the housing market, young single-person households are facing an increasingly pronounced mismatch between their housing needs and their actual access to housing. Based on statistical data released by the Ministry of Health, Labour and Welfare of Japan, as shown in Figure 2a, the data

for 2009 were excluded from the analysis due to their absence from the official website. Nevertheless, the data from the past two decades still reveal a clear trend: the average homeownership rate among single residents under the age of 34 was only 5.34%, which is far lower than the corresponding average of 54.87% for the overall single-resident population. As shown in Figure 2b, the average proportion of housing expenditure in total consumption expenditure among young single residents under the age of 34 over the past two decades was 20.19%, whereas the corresponding figure for other single-person households was 13.53%. This indicates that, compared with other single residents, young single people are in a more disadvantaged position in the housing market. At the same time, housing expenditure among young single residents fluctuates considerably, suggesting that they are more sensitive to changes in the housing market and are in a relatively vulnerable position. This further indicates that the level of investment made by young single-person households in housing substantially exceeds their actual capacity for ownership. In addition, the market supply of housing products targeting young consumers remains insufficient, and such products often fail to meet young people's expectations in terms of residential environment, lifestyle-related amenities, and personalization [5,26,28]. This phenomenon suggests that, although young people generally show a strong willingness to purchase housing, multiple constraints have contributed to a generally low level of satisfaction with existing housing conditions.

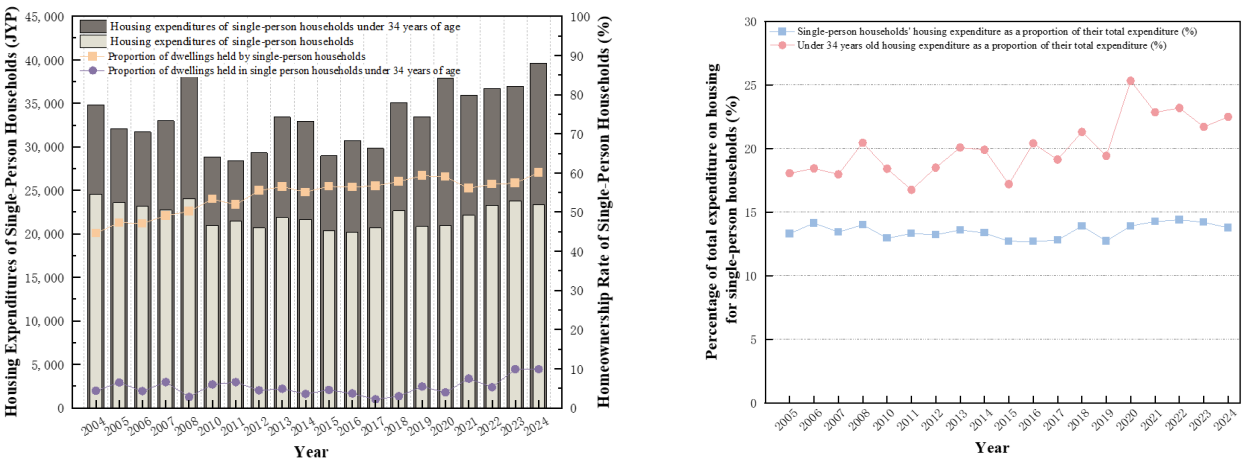


Figure 2. Housing tenure and housing expenditure trends among single residents under 34 in Japan, 2005–2024. (**a**) Homeownership rate and per capita housing expenditure. (**b**) Housing expenditure as a share of total consumption expenditure.

In view of the background outlined above, this study selected residential projects currently under development in the urban area of Fukuoka City, in northern Kyushu, Japan, for simulation-based experimentation. Fukuoka City is the most populous city on the island and the sixth-largest city in Japan, and together with Kitakyushu City, it constitutes the two major metropolitan areas of northern Kyushu and Fukuoka. According to Japan's *Basic Plan for Housing and Living*, the induced residential area standard refers to the necessary dwelling area required to achieve a comfortable standard of living in apartment housing located in urban centers and their surrounding areas. For Fukuoka City as a metropolitan area, the minimum required dwelling area is 40 m^2 for single residents, while for households of two or more persons, the required area is calculated as 20 m^2 × number of residents + 15 m^2. Based on these criteria, a search of local real estate agencies and the SUUMO housing platform identified 31 apartment-type residential units for sale, including both those under construction and those not yet built, within the range of 40 to 55 m^2, using a

one-square-meter interval as the screening unit. Among them, eight units fell within the 43–44 m^2 range (Plan 1–Plan 8), accounting for 25.8% of the total. The basic conditions of these eight floor plans are shown in Figure 3, and their area data are summarized in Table 1. The primary floor plan types were one-bedroom units with a living, dining, and kitchen area (1LDK) and two-bedroom units with a living, dining, and kitchen area (2LDK). Therefore, residential units within this size range were adopted as the research samples in this study.



Figure 3. Floor plans of the eight sample residential units.

Table 1. Size distribution of spatial units.

Basic Data on Units	P1	P2	P3	P4	P5	P6	P7	P8
Type of unit	2LDK	2LDK	2LDK	2LDK	1LDK	2LDK	1LDK	2LDK
LDK (Living + Dining + Kitchen)	18.63	16.6	16.15	14.74	19.92	16.7	18.32	16.26
MB (Main Bedroom)	6.46	7.3	6.51	8.14	8.14	8.05	8.4	7.3
GB (Guest Bedroom)	4.88	5.2	5.98	6.14	0	4.86	0	5
BA (Bathroom)	3.04	3.04	3.04	3.04	3.04	3.4	3.4	3.4
Type of BA	1216	1216	1216	1216	1216	1317	1317	1317
PR (Powder room)	2.65	2.81	3.57	3.82	2.97	3.84	2.84	3.37
TO (Toilet)	1.93	1.83	1.3	1.23	2.4	1.35	2.25	1.73
SR (Storage)	2.79	1.96	3.59	2.55	4.15	2.9	5.2	2.93
EH (Entrance Hall)	2.64	4.38	3.2	3.83	3.11	2.69	3.41	3.93
BL (Balcony)	9	8.7	8.9	7.94	7.01	5.1	4.8	5.89
Total Floor Area	43.02	43.12	43.34	43.49	43.73	43.79	43.82	43.92

3.1.2. Evaluation and Quantitative Analysis of Floor Plan Attributes

In residential architectural design research, the planar attributes of housing design involve a wide range of data types, making it difficult to conduct a systematic evaluation based on a single standard. Therefore, a quantitative description of residential floor plans is particularly important for accurately understanding the preferences of potential users. A

review of the literature on evaluation indicators for residential floor plan layouts shows that comfort-related factors, such as daylighting and ventilation in the living and dining area and the proportion of south-facing room area, as well as practicality-related factors, such as the proportion of entrance hall area, balcony area, and overall space utilization, are the principal indicators in most residential floor plan evaluation systems.

Based on residential modeling and statistical analysis of the relevant data, this study identified key housing attributes and grouped them into three categories: function, spatial relationship, and comfort, as shown in Table 2. The selection of these indicators was primarily guided by three considerations: whether they can be easily quantified, whether they are suitable for evaluating floor plans at the early design stage, and whether they exhibit meaningful differences across design proposals.

Table 2. Descriptive Statistics of Key Variables for the Sample Residential Designs.

		P1	P2	P3	P4	P5	P6	P7	P8
	1. Function								
Available space	LDK Area	16.82	18.63	16.52	16.20	14.74	19.93	16.69	18.31
	MB Area	6.46	7.30	6.51	8.14	8.14	8.05	8.40	7.30
	EH-to-floor area ratio (EHFR)	0.061	0.102	0.074	0.088	0.071	0.061	0.078	0.089
	BL-to-floor area ratio (BLFR)	0.173	0.168	0.170	0.154	0.138	0.104	0.099	0.118
	SR Count (SRC)	3	3	3	2	2	3	2	3
	Total room count (TRC)	11	11	10	10	9	11	9	11
	2. Spatial relationships								
Distance of space [a]	Dis (MB, BA)	9.07	5.49	7.82	7.75	6.88	5.92	10.67	11.81
	Dis (PR, BL)	11.29	9.33	10.23	8.29	7.59	7.75	10.10	5.94
Depth of spaces	EH depth (EHD)	1.8	2	1.78	1.45	1.88	2	1.63	1.8
	Hillier–Hanson (HH) integration value of MB (IHMB)	1.02	1.04	0.85	0.98	1.11	1.11	0.81	0.88
	3. Comfort								
Natural light	Bedroom window count (BWC)	1	1	2	2	2	2	2	2
	Living-room orientation (LRO)	NE	NW	SE	E	NW	SE	SE	N
	MB window-to-floor ratio (MB WFR)	0.29	0.41	0.37	0.31	0.31	0.35	0.32	0.41
	LDK window-to-floor ratio (LDK WFR)	0.15	0.38	0.23	0.33	0.32	0.44	0.23	0.19
	South-facing floor-area ratio (SFAR)	0	0.55	0.52	0.33	0.64	0.49	0.61	0.48
Ventilation	Actual distance from EH to BL windows [b]/Euclidean distance (AEDR)	1.075	1.098	1.100	1.139	1.307	1.261	1.190	1.065

[a] dis (m, n) means the walking distance along 0, 45, 90 and 135 degree lines between the geometric centers of spatial units m and n. [b] Measured from the mid-points of the windows of EH and BL in the floor plans.

Privacy Analysis of Residential Layouts Using Space Syntax

In the fields of residential design and living experience research, "privacy", as a dynamic topological attribute of space, has long been discussed yet often underestimated because of its latent nature. However, it is now widely recognized as a core dimension of residential livability, one that is as important as ventilation, daylighting, and safety [29,30]. Therefore, privacy should be regarded as a controllable design variable rather than an incidental outcome that emerges after spatial form has been determined.

To transform privacy into a quantifiable indicator, this study employed DepthmapX (version 0.8.0), a space syntax analysis tool developed by University College London (UCL), to evaluate the privacy performance of residential layouts through spatial configuration analysis. This approach avoids relying solely on designers' intuitive perceptions or experience-based judgments, thereby making privacy analysis more objective and precise. At the same time, space syntax was used to assist designers in testing design proposals, predicting potential design outcomes, and evaluating spatial structures through quantita-

tive and scientifically grounded data. Space syntax does not rely solely on visibility; it also considers the degree of difficulty involved in reaching different rooms or areas. This makes it possible to determine the "depth" of a building from a given point and to organize space according to accessibility. Parameters such as mean depth (MD), integration value, and relative asymmetry (RA) can further reveal the complexity of a layout [31,32].

As illustrated in Figure 4, each spatial unit was abstracted as a node. Based on the space syntax framework established by Hillier and Hanson in "*The Social Logic of Space*" [33], the connectivity between spatial units was operationalized in this study as follows: units connected by a door were assigned a depth value of 1, whereas directly adjacent units without a door connection were assigned a depth value of 0.5. The depth between any two units, m and n, denoted as dep(m,n), is defined as the sum of the connection depths along the path linking them, as shown in Figure 4b. On this basis, EH Depth (EHD), defined as the average depth from the entrance hall to all spatial units, was calculated to characterize the spatial hierarchy of the floor plan (Table 2).

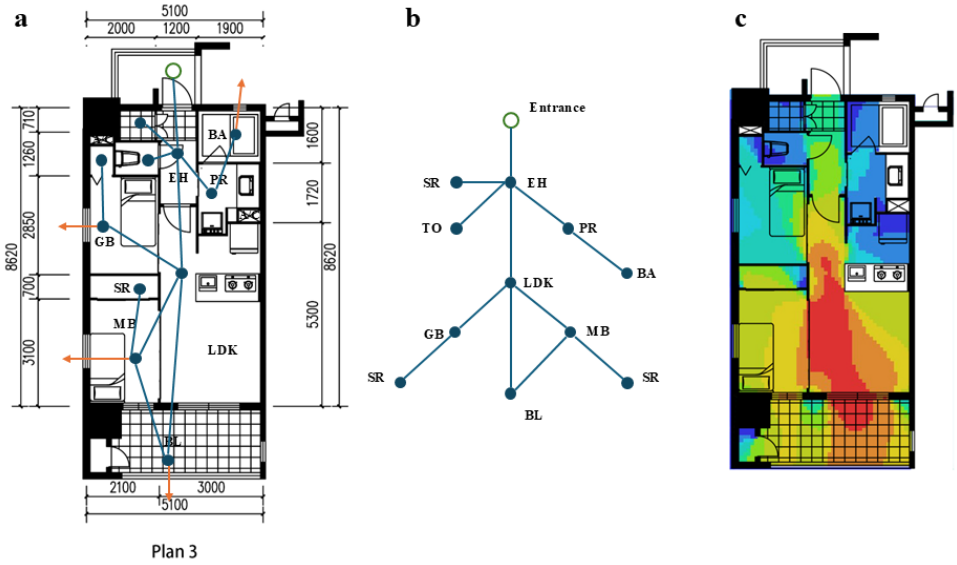


Figure 4. Spatial hierarchy and privacy analysis of Plan 3: (**a**) floor plan and spatial unit network; (**b**) topological representation of spatial depth based on the door connection model; and (**c**) privacy visualization generated by DepthmapX.

Using DepthmapX, a privacy visualization of each residential layout was generated, as shown in Figure 4c. In addition, the integration value of the master bedroom in each residential unit was calculated (Table 2). A number of space syntax studies have shown that integration, as an important indicator of the accessibility or centrality of a space within a spatial network, has a significant influence on residential privacy. In general, a lower integration value indicates a more segregated spatial position and lower accessibility within the layout, which can reduce visual exposure and strengthen the privacy of domestic spaces [25,34]. Therefore, a well-designed residential layout should achieve a balance between accessibility and privacy in order to satisfy the diverse needs of residents [31,35].

Analysis of Residential Floor Plan Attributes Using Principal Component Analysis

Since Marans and Rodgers (1975) [36] first applied principal component analysis (PCA) with Varimax rotation to more than 60 items of community satisfaction in the Detroit area and condensed them into six core dimensions of satisfaction, a methodological foundation for the "dimension reduction + decision-making" paradigm was established. Cook (1988) [37], focusing on a specific user group, further reduced 20 indicators of neighborhood perception into five principal factors, highlighting the multidimensional structure

of satisfaction and improving the robustness of the model. Since then, a large body of research has followed the workflow of "PCA-based dimension reduction–factor naming–visualization/prediction" to condense complex housing attributes, environmental quality, and socioeconomic indicators into a small number of composite dimensions, making this approach an indispensable core method in residential satisfaction research.

Building on previous studies, this section employs PCA to quantify and categorize the attributes of residential floor plans into a smaller number of dimensions. A comparison of the eight groups of physical indicators for residential floor plans shown in Tables 1 and 2 reveals that the layout of a single residential unit constitutes a highly integrated system, within which many indicators and dimensions are strongly correlated. As a result, direct analysis of residential floor plans would be both time-consuming and prone to multicollinearity. To address this issue, IBM SPSS Statistics (version 30.0) was used to test the correlations among the eight groups of residential samples shown in Tables 1 and 2. Variables such as living-room orientation were considered unsuitable for PCA because their categorical nature would be converted into meaningless quantitative scales during computation. To avoid this problem, qualitative categorical variables were recoded into binary variables. Based on a comprehensive examination of inter-variable correlations and overall variance, eight variables were ultimately selected, as shown in Table 3. These variables have absolute Pearson correlation coefficients of less than 0.7 with the remaining indicators, indicating relatively low dependence while still accurately capturing the diversity of the floor plans.

Table 3. Principal Component Analysis Results for Floor Plan Attributes.

	Eigenvectors of Principal Components			**Rotated Factor Loadings**		
Variables	**PC1**	**PC2**	**PC3**	**1. Privacy**	**2. Comfort**	**3. Functionality**
Total Area	0.085	0.903	−0.004	−0.236	0.875	0.037
MB Area	0.397	0.751	−0.483	0.222	0.889	−0.337
Dis (MB, BA)	−0.848	0.400	0.128	−0.936	0.082	−0.109
EH depth	0.626	−0.317	0.523	0.540	−0.152	0.672
Integration Hillier–Hanson of MB	0.753	−0.405	−0.338	0.907	−0.094	−0.119
MB window-to-floor ratio	0.209	0.124	0.908	−0.089	0.080	0.932
LDK window-to-floor ratio	0.935	0.119	−0.131	0.836	0.432	0.140
South-facing floor-area ratio	0.465	0.713	0.347	0.082	0.781	0.477
Eigenvalue	2.976	2.341	1.599			
Per cent	37.205	29.268	19.985			
Cum. Per cent	37.205	66.474	86.459			

The retained variables were as follows:

1. Total Floor Area
2. Main bedroom (MB) Area
3. Distance between MB,BA (Dis (MB,BA))
4. EH depth
5. Hillier–Hanson (HH) Integration value of MB
6. MB window-to-floor ratio (MBWFR)
7. LDK window-to-floor ratio (LDKWFR)
8. South-facing floor area ratio (SFAR)

Figure 5 illustrates the workflow of the PCA-based quantitative analysis of residential floor plan attributes. Principal component analysis was conducted using the eight variables

described above. To eliminate differences in scale and magnitude among the variables, all retained variables were first standardized, as shown in Equation (1) and Figure 5:

$$z_{ij} = \frac{x_{ij} - \overline{x}_j}{s_j} \tag{1}$$

where x_{ij} denotes the observed value of the indicator j for floor plan sample i, $\overline{x}_j$ denotes the sample mean of the j-th indicator, s_j denotes the sample standard deviation of the j-th indicator, and z_{ij} denotes the standardized value.

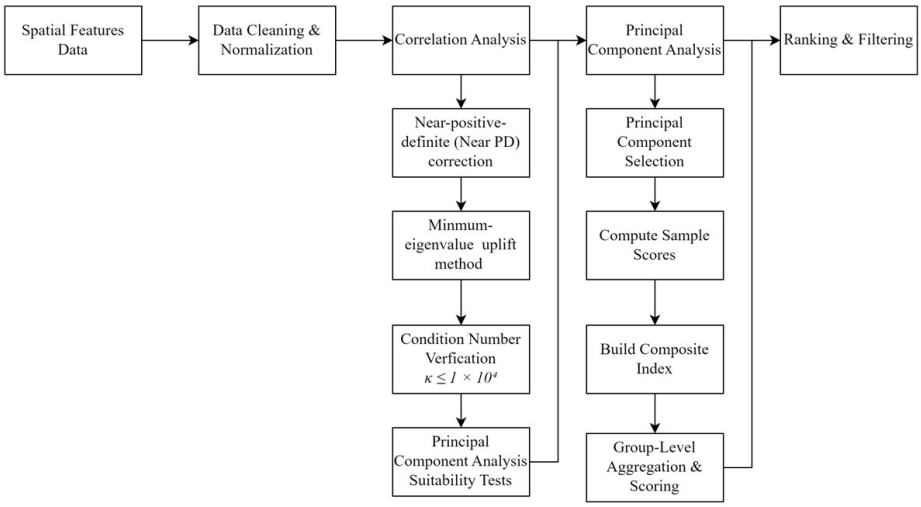


Figure 5. Workflow of PCA-based quantitative analysis of residential floor plan attributes.

Using the standardized data, a sample correlation matrix was constructed as:

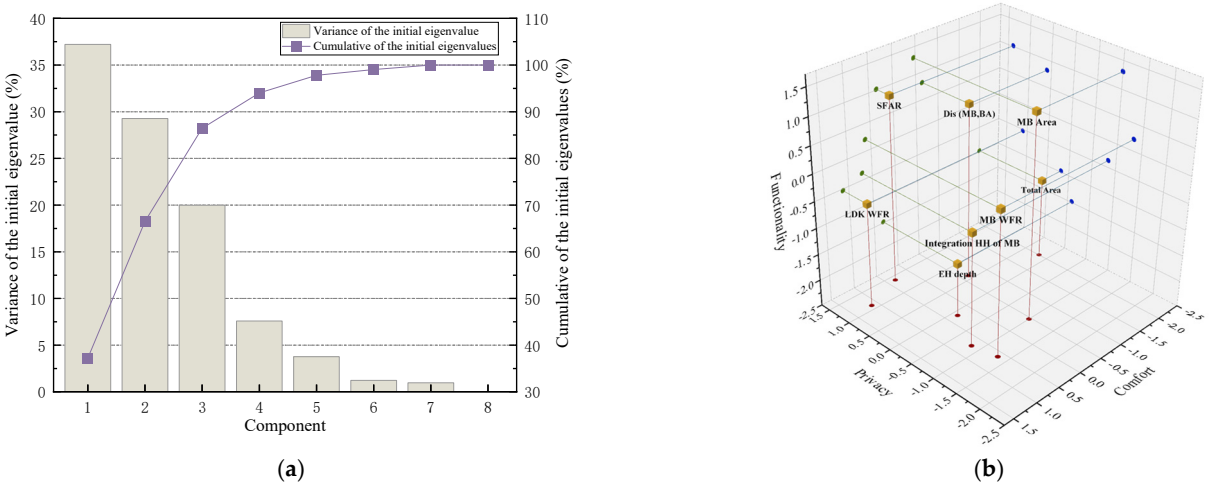
$$R = \frac{1}{n-1} Z^T Z$$

where $Z = [z_{ij}] \in \mathbf{R}^{n \times p}$ denotes the standardized data matrix, n is the number of floor plan samples, and p is the number of retained variables. In this study, $n = 8$ and $p = 8$. This dataset, therefore, represents a small-sample, high-dimensional boundary case with $p \geq n$ [38,39]. Because the standardized matrix is column-centered, its rank satisfies $\text{rank}(Z) \leq n - 1$, and thus the sample correlation matrix also satisfies $\text{rank}(R) \leq n - 1$. In the present case, this implies $\text{rank}(R) \leq 7 < p = 8$, meaning that the sample correlation matrix is rank-deficient and cannot be guaranteed to be strictly positive definite. Under such conditions, conventional PCA may suffer from numerical instability during eigen decomposition.

To address this issue (Figure 5), a near-positive-definite (Near-PD) was applied to the sample correlation matrix following Higham (1988) [40]. This procedure was used as a numerical regularization step to obtain a stable matrix for subsequent PCA. In addition, a minimum-eigenvalue reconditioning procedure was adopted following Tabeart et al. [41] to improve matrix invertibility and conditioning. Strict symmetric positive definiteness (SPD) of the corrected matrix was then verified using non-pivoted Cholesky factorization [42]. Here, the Near-PD correction and minimum-eigenvalue uplift should be understood as numerical stabilization procedures rather than substantive transformations of the original floor plan attributes, and no physical interpretation was assigned to any additional components associated with zero or near-zero eigenvalues.

After numerical stabilization of the correlation matrix, principal component analysis was performed using the eight selected variables. Three principal components with eigen-

values greater than 1 were extracted, as shown in Figure 6a. Together, these components explained 86.46% of the total variance. Hair et al. [43] suggested that, in social science research, a cumulative explained variance of 60% or above is generally acceptable, while 70–80% is commonly regarded as the ideal range. Therefore, the cumulative explained variance achieved in this study exceeds the basic requirement [39,44,45] and can be considered to capture most of the underlying information. The detailed results are presented in Table 3.



(**a**) (**b**)

Figure 6. PCA results of residential floor plan attributes: (**a**) scree plot and cumulative explained variance of principal components; (**b**) three-dimensional loading distribution of variables on the first three principal components.

Using SPSS, the three principal components were rotated, and three dimensions were identified according to their correlations with the original variables, as shown in Figure 6b, with the detailed results reported in Table 3. After rotation, PC1 was strongly positively correlated with Integration Hillier–Hanson of MB (0.907), LDK WFR (0.836), and spatial depth (0.540), while showing a strong negative correlation with Dis (MB, BA) (−0.936). Taken together, these variables reflect differences in the separation between private and service spaces, as well as in spatial exposure and visual shielding. Therefore, PC1 was interpreted as a privacy-related dimension. For ease of interpretation in a positive direction, the sign of PC1 was reversed in the subsequent calculations so that a higher score would indicate a higher level of privacy. PC2 was strongly correlated with net internal area (0.875), master bedroom area (0.889), and the proportion of south-facing daylighting area (0.781), while showing a negative correlation with spatial depth from the entrance (−0.152). Larger indoor areas, together with better daylighting and ventilation conditions, jointly indicate the physiological and psychological comfort of the dwelling. Accordingly, PC2 was interpreted as comfort. PC3 was positively correlated with the window-to-floor ratio of the master bedroom (0.932) and spatial depth from the entrance (0.672) and negatively correlated with the distance between the master bedroom and the bathroom (−0.109). This component mainly reflects spatial proportions and functional circulation, both of which are closely related to the basic efficiency of spatial use. Therefore, PC3 was defined as functionality.

Based on the corresponding principal component scores, the sample scores of the residential floor plan types were calculated using the regression method [46], as shown in Equation (2):

$$F_{ik} = \sum_{j=1}^{p} b_{jk} z_{ij} \quad (2)$$

where F_{ik} denotes the score of the sample i on principal component k, z_{ij} denotes the standardized value of the variable j for sample i, and b_{jk} denotes the factor score coefficient of the variable j on principal component k.

To facilitate subsequent interpretation of the data and to maintain consistency with the direction of the other two principal components, a higher score was defined to indicate stronger privacy. Therefore, the privacy factor score was multiplied by -1, yielding FAC1-1. The contribution percentages of the three principal components were then converted into weights, as shown in Equation (3):

$$w_k = \frac{v_k}{\sum_{k=1}^{m} v_i} \tag{3}$$

where w_k is the weight of the k-th principal component, v_k is the proportion of variance explained by the k-th principal component after rotation, and m is the number of retained principal components.

Based on these weights, the composite score of each sample floor plan was calculated using Equation (4):

$$S_j = \sum_{k=1}^{m} w_k F_{ik} \tag{4}$$

where S_i is the composite score of the i-th sample floor plan.

Using a quantitative approach based on PCA, the eight sample floor plans were evaluated from three dimensions: privacy, comfort, and functionality. To maintain consistency between the total score and the explanatory power of the principal components, this study adopted the proportion of explained variance after rotation, as shown in Equation (3), as the weighting criterion, and performed a linear weighted aggregation of the scores for the eight sample floor plans to obtain the final composite evaluation index. The resulting ranking of the eight sample floor plans was as follows: P8 > P7 > P3 > P5 > P2 > P4 > P6 > P1.

Overall, the higher-ranked floor plans tended to show a better balance across the three dimensions, whereas the lower-ranked floor plans often exhibited a clear weakness in one key dimension, which in turn reduced their overall scores. Among the eight sample floor plans, P8 and P7 achieved the best overall performance. This was mainly because their corridor organization, partition walls, and longitudinal layout created a clearer spatial hierarchy, allowing for better topological distance and visual buffering between private and public spaces, which contributed to their higher scores in the privacy dimension. At the same time, both plans also performed well in indicators such as master bedroom area, daylighting conditions, and window-to-floor ratio, reflecting relatively strong comfort and functionality. In contrast, although P3 and P5 each showed certain advantages in either privacy or comfort, their overall balance was comparatively weaker, and they therefore ranked in the middle. P2, P4, and P6, by comparison, revealed imbalances across different dimensions. P2 scored relatively high in functionality, but its privacy was constrained by insufficient separation between active and quiet zones and weak topological shielding. P4 showed a moderate level of comfort, but its relatively low window-to-floor ratio in the master bedroom and shallow spatial depth from the entrance weakened its functional performance. Although P6 performed relatively well in comfort, its privacy was weak, indicating that floor area or localized comfort conditions alone are not sufficient to compensate for deficiencies in spatial organization. P1 received the lowest overall score, mainly because it did not demonstrate clear advantages in area, daylighting, ventilation, or spatial organization, and therefore remained in a disadvantaged position across all three dimensions.

Overall, the comprehensive evaluation of small- and medium-sized dwellings does not depend on the optimization of any single indicator, but rather on the coordination

and balance among privacy, comfort, and functionality. Compared with simply increasing floor area or the number of rooms, a more rational spatial hierarchy, better daylighting and ventilation conditions, and higher basic space-use efficiency are the key factors in improving the overall residential quality.

3.2. Experimental Design

Based on the PCA and linear weighted composite scoring method described in Section 3.1.2, this study established a quantitative framework of physical attributes for the eight sample floor plans across three dimensions—privacy (PC1), comfort (PC2), and functionality (PC3)—and produced a ranking of their overall performance (see Table 4). However, from the user's perspective, relying solely on design-side physical indicators may not be sufficient to ensure that this ranking accurately reflects the subjective preferences of potential users [21,47]. In the context of this research, immersive virtual reality can serve as a communication medium in the AEC industry to connect designers with potential residents, thereby testing how users understand architectural representations. On this basis, and building on the quantitative model, a comparative experiment was further designed as follows:

1. Traditional 2D environment: Participants were presented with floor plans together with three-dimensional models displayed on a computer monitor.
2. Immersive VR environment: Participants were presented with virtual floor plan scenes through a head-mounted display, in which they could walk freely and interact with the environment in real time.

Table 4. Scores and Composite Evaluation Results of the Eight Floor Plans.

	FAC1	FAC2 (Comfort)	FAC3 (Function)	FAC1-1 (Privacy)	Total Score
P1	−0.17561	−2.00334	−0.97237	0.17561	−0.83
P2	1.00006	−0.46024	1.30993	−1.00006	−0.28
P3	−0.59628	−0.64089	0.81212	0.59628	0.23
P4	0.10227	0.30386	−1.47889	−0.10227	−0.28
P5	0.83680	0.71344	−0.36869	−0.83680	−0.20
P6	1.32536	0.61829	0.21413	−1.32536	−0.31
P7	−1.10541	1.12280	−0.53049	1.10541	0.73
P8	−1.38719	0.34608	1.01426	1.38719	0.95

Before the formal experiment, participants were first given a brief introduction to the study and completed the informed consent form. They then filled out the basic demographic questionnaire and were provided with an example floor plan to explain the rating criteria and operational procedures. To reduce bias caused by learning and adaptation, a 10 min device and interaction training session was arranged, and the data from this training session were not included in the analysis.

In the formal experiment, as shown in Figure 7, a within-subjects design was adopted, in which each participant evaluated all eight floor plans under both experimental conditions. To reduce order and carryover effects, the sequence of the experimental conditions was counterbalanced and randomized. Specifically, participants were randomly assigned to one of two experimental sequences: half of the participants completed the Traditional 2D condition first and then the immersive VR condition, whereas the other half completed the immersive VR condition first and then the Traditional 2D condition. Therefore, any improvement in spatial understanding resulting from prior exposure to the same floor plans was not systematically attributed to a single presentation medium. This within-

subjects design also helped control for individual differences associated with repeated measurements [48,49].

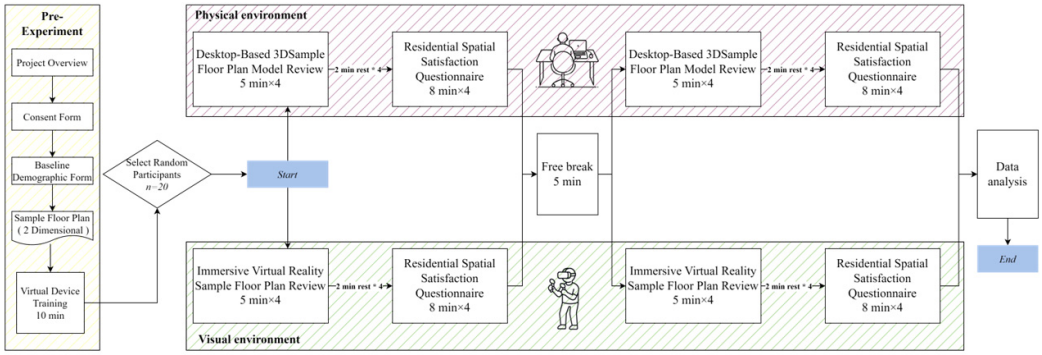


Figure 7. Workflow of the Comparative Experiment in the Traditional 2D and Immersive VR Environments.

The evaluation of each floor plan consisted of two stages: model viewing, which lasted approximately 5 min, and residential satisfaction assessment using the RSSQ, which lasted approximately 8 min. A 2 min break was arranged between floor plans, and a 5 min washout break was provided after every four evaluations. If any discomfort occurred, participants were allowed to pause or withdraw from the experiment at any time. To reduce recall bias, participants were required to complete the RSSQ immediately after viewing each model, recording their overall preference as well as subscale scores related to privacy, comfort, and functionality. When item-level missing data were less than 10%, mean imputation within the same dimension for the same participant was applied; when missing data reached 10% or more, the data for that dimension were excluded from the analysis. The experimental procedure is shown in Figure 7. This procedure was designed to support the research questions proposed in Section 2.4 by enabling a direct comparison between the Traditional 2D environment and the immersive virtual environment.

3.2.1. Experimental Participants

A total of 20 students were planned to be continuously recruited from the Department of Environmental Engineering at the University of Kitakyushu, Japan, through posters and on-site publicity. The target sample size was determined with reference to previous studies in AEC design review and spatial perception, particularly those related to Virtual Reality–Human Computer Interaction (VR-HCI) and immersive architectural evaluation, in which sample sizes typically range from 10 to 30 participants [50,51]. In the present study, participants were required to complete repeated spatial perception, navigation, interaction, and evaluation tasks under controlled experimental conditions when comparing the Traditional 2D environment with the immersive virtual environment. Considering the aims of this study, the need to reduce between-participant variability, and the feasibility of repeated model viewing, navigation, interaction, and questionnaire-based evaluation, the sample size was set at approximately $n = 20$. This setting is consistent with common practice in VR-HCI-related and immersive architectural evaluation studies. One participant was excluded during the pilot experiment due to obvious VR motion sickness. As a result, 21 participants were recruited in total, and valid data from 20 participants were included in the final analysis. The eligibility criterion for age was 24–35 years. This range was selected because the target population of this study was potential young residents. After graduating from university at around the age of 23, young adults begin to face more independent living situations, develop stronger housing needs, and tend to consider residential functionality in a more mature manner. The gender composition of the final sample was 13 males and

7 females. In accordance with the requirements of the "*Regulations on the Prevention of Misconduct in Research Activities*" of the University of Kitakyushu, participants were informed in advance that their data would be used for academic research, and informed consent was obtained from all participants. Participation was entirely voluntary, and participants were also informed that they could withdraw at any time and that all data would be anonymized.

3.2.2. Traditional 2D Visualization Environment

The Traditional 2D visualization condition was developed based on the sample residential floor plans selected in Section 3.1.1. First, drawings with accurate dimensions were produced in AutoCAD 2025 and then imported into SketchUp 2025 for three-dimensional modeling. The interior floors and walls were arranged according to configurations commonly used in Japanese housing, and the spaces were furnished in accordance with the furniture layout provided in the floor plans. In addition, the material settings and furniture models were standardized across all sample residential models in order to ensure that comparisons between different floor plans were focused as much as possible on the differences in plan configuration itself. The 3D models were then rendered in real time using a high-performance workstation, presented to the participants, and followed by questionnaire feedback based on users' actual spatial experience.

The workstation used in the experiment had the following hardware configuration: an Intel(R) i7-12700H CPU and an NVIDIA 3060 GPU. Participants reviewed and evaluated the design schemes on a standard display device with a full-HD display and a refresh rate of 165 Hz.

3.2.3. Immersive Virtual Environment

The immersive virtual environment experiment was likewise based on the sample residential floor plans selected in Section 3.1.1, and its virtual scene models were kept consistent with those used in the Traditional 2D visualization experiment described in Section 3.2.2. The virtual experiment was conducted using a Meta Quest 2 head-mounted display (Meta Platforms Technologies, LLC, Menlo Park, CA, USA), and real-time navigation of the virtual scenes was implemented through the Enscape plug-in in SketchUp, as shown in Figure 8. In addition, the 2D visualization models and the immersive VR environments were developed using the same basic material settings, including furniture layouts, lighting baselines, wall colors, floor finishes, and interior decorative styles, and these settings were kept consistent across the eight floor plans. The layout and material representation of the models were therefore standardized to control for factors other than the presentation medium [52,53]. This ensured that participants' evaluations focused primarily on differences in floor plan configuration, spatial hierarchy, circulation routes, privacy, and functional organization, rather than on individual preferences for interior decoration styles, thereby maintaining the comparability of the two experimental conditions.

To enhance the realism of scene representation and to standardize environmental variables, the daylighting conditions of all virtual residential models were set to the lighting scenario corresponding to the minimum solar altitude angle on the winter solstice. This lighting setting was selected because residential layouts are often influenced by daylighting requirements, which commonly use the winter solstice as a reference date for ensuring sufficient sunlight in key living spaces such as bedrooms and living rooms [54]. As the winter solstice represents the lowest annual solar altitude, it provides a relatively unfavorable but conservative daylighting condition for residential evaluation. This helped avoid overestimating spatial satisfaction under overly ideal daylight conditions and ensured that all eight floor plans were assessed under the same environmental baseline [52]. By applying the same lighting environment, differences in the atmosphere of different interior

spaces could be compared under consistent conditions. In addition, during navigation in the virtual environment with the Quest 2 headset, the viewpoint height was uniformly set at 170 cm to simulate the everyday spatial perception of an adult in a residential setting and to reduce spatial cognitive bias caused by differences in viewpoint height. During the experiment, participants were allowed to move freely and observe the space using handheld controllers. In addition to the roaming function, doors and windows in the virtual scenes could also be opened and closed, thereby enhancing participants' perception of spatial openness, boundary relationships, and indoor environmental conditions.

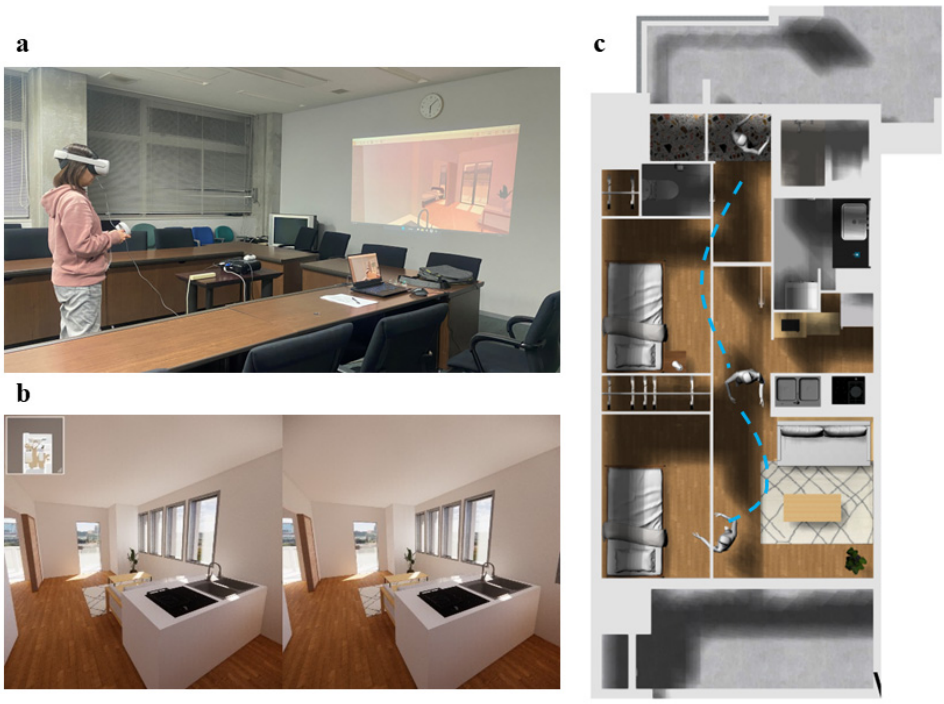


Figure 8. Experimental setup of the immersive virtual environment: (**a**) participants' virtual experimental environment; (**b**) rendered view of the virtual environment in the VR headset; (**c**) approximate walking route in the virtual environment.

3.2.4. Questionnaire Design and Analytical Methods

This study imposed clear constraints on both the experimental environment and the participant group and adopted two questionnaires. Questionnaire A was used to collect demographic information, while Questionnaire B was the Residential Spatial Satisfaction Questionnaire (RSSQ). The two questionnaires served complementary functions in this study: Questionnaire A was used to characterize the sample structure and participants' functional needs, whereas Questionnaire B was used to obtain subjective satisfaction evaluations of specific floor plans.

- Questionnaire A: Demographic Information and Functional Importance

Questionnaire A was used to collect participants' basic demographic information, including age, gender, educational background, and current living arrangement, and required participants to rank the importance of major spatial functions, such as the LDK, bedroom, storage, and bathroom. This questionnaire was intended not only to reflect individual-level functional needs but also to provide contextual support for the interpretation of subsequent results.

For the ranking of major spatial functions, the rank q_{ij} assigned by participant i to function j (1 = most important, 9 = least important) was converted into a Borda score as follows:

$$S_{ij} = m - q_{ij}, (m = 10) \quad (5)$$

The scores for each function were then summed across all participants. To facilitate comparison, the total scores were further normalized into percentage weights:

$$w_j = \frac{\sum_i S_{ij}}{\sum_j \sum_i S_{ij}} \times 100\% \quad (6)$$

where q_{ij} denotes the rank assigned by the participant i to function j, S_{ij} denotes the corresponding Borda score, m denotes the total number of rank positions plus one $(m = 10)$, and w_j denotes the normalized percentage weight of the function j across all participants.

The overall differences were tested using the Friedman test, and Kendall's W was used to examine the consistency of the preference rankings.

Previous studies have shown that residential satisfaction and preference are significantly influenced by family life cycle and individual attributes, while the weights assigned by individuals to functional attributes systematically shape their evaluations of dimensions such as room quantity, layout, and privacy [27,55]. Therefore, Questionnaire A served three main purposes in this study: (1) statistical description of basic information, which was used to characterize the sample and provide contextual support for the interpretation of subsequent results; (2) quantification of functional needs, in which the subjective importance of spatial functions was converted into comparable weights to explain the variation that might occur in the evaluation of the same floor plan across different participants; and (3) enhancement of external validity, as reporting participant characteristics and functional priorities made it possible to compare this sample with existing studies of a similar type. In addition, to further strengthen external validity, the present sample focused on young people with an intention to live independently, whose functional needs and housing preferences have been well documented in the literature [16].

- Questionnaire B: RSSQ, Reliability, and Data Analysis

Questionnaire B (RSSQ), as shown in Table 5, was developed by the authors on the basis of studies on unit-level satisfaction in the literature on residential satisfaction and environmental psychology [55], and its scale development and scoring followed psychometric principles [56]. In line with the physical framework established earlier through PCA—privacy, comfort, and functionality—the RSSQ consisted of 13 items organized into three latent dimensions.

The RSSQ was designed to obtain comparable subjective ratings of key dimensions, including the quantity and composition of housing units, spatial layout, privacy, and comfort, under the two presentation conditions of the Traditional 2D environment and the immersive VR environment by using the same set of items. This provided reliable data for testing consistency and convergent validity against the physical framework established through PCA. The combined use of the two approaches enabled this study not only to identify media effects but also to reveal the relationships among individual needs, subjective evaluations, and physical attributes, thereby providing more methodologically rigorous evidence for user-centered residential design evaluation.

All RSSQ items were rated on a 5-point Likert scale (1 = very dissatisfied/strongly disagree, 5 = very satisfied/strongly agree). The score for each dimension was calculated as the arithmetic mean of the corresponding items, and the overall ranking was further converted into rank scores. To evaluate the measurement quality of the RSSQ in the present sample, the internal consistency and convergent validity of each dimension were assessed

at three data levels: ALL, 2D, and VR. Internal consistency was evaluated using Cronbach's α and McDonald's ω. In general, internal consistency was considered acceptable when α or $\omega \geq 0.70$ [57,58]. Convergent validity was assessed using the average variance extracted (AVE), with AVE ≥ 0.50 indicating good convergent validity [55]. By comparing α, ω, and AVE across the ALL, 2D, and VR datasets, the structural stability of the RSSQ under different presentation conditions could be examined, thereby providing a basis for the subsequent analysis of media effects.

Table 5. Item Structure of the Residential Spatial Satisfaction Questionnaire (RSSQ).

PCA Dimensions	Item No.	Question	Dimension Rationale
PC1 Privacy	Q9	What do you think of the privacy of the master bedroom?	Measure the privacy of the MB
	Q12	What do you think of the separation of circulation between the bedroom and the visitor/housework routes?	Route privacy
	Q13	What do you think of the visual buffering between the bedroom and LDK (e.g., vestibule/corridor/offset)?	Visual screening/Visual privacy
PC2 Comfort	Q1	Size of total area	Reflects overall spatial comfort
	Q2	Size of LDK area	Usability and comfort of the LDK
	Q3	Size bedroom area	Bedroom activity space and sleep comfort
	Q4	Size of bathroom area	Spatial comfort of the bathroom
	Q10	Natural lighting of the master bedroom	Comfort of natural lighting
	Q11	Direction/orientation of living room	Effects of orientation on solar exposure, ventilation, and thermal comfort
PC3 Functionality	Q5	Size of SR	SR capacity
	Q6	Number of rooms	Programmatic functionality of the plan
	Q7	Number of bedrooms	Configuration of sleeping functions
	Q8	Number of storage spaces	Dispersion of SR

4. Results and Discussion

4.1. Participant Characteristics

As shown in Table 6, analysis of the questionnaire data indicated that the participants' current average living area was 26.68 m^2 (SD = 10.5, n = 20), which was smaller than the target residential area adopted in this experiment. In addition, 90% of the participants had background knowledge or relevant experience in architecture and related fields, suggesting that they had no obvious difficulty in understanding the experimental procedure or completing the questionnaire. Only 5% of the participants reported brief prior experience with VR, indicating that the immersive virtual environment was still relatively novel for most of them. During the virtual environment simulation experiment, 35% of the participants experienced different degrees of motion sickness; however, after a short rest, they were generally able to recover and complete the test. All participants evaluated all eight design schemes under both experimental conditions.

Table 6. Demographic and experimental characteristics of participants.

Attribute	Value (n = 20)
Age range	24~35 years
Mean age	29.2 ± 3.4 years
Gender	
Male	65%
Female	35%
Educational level	
Undergraduate degree	10%
Master's degree	35%
PhD degree	55%
Major	
Architecture and Environmental Engineering	90%
Other professions/Lay people	10%
Others	
With color blindness	-
With motion sickness in the VR experiment	35%
With experience in virtual environment	5%
Average current living area	26.68 ± 10.5

Based on the Borda scores of the 20 participants, the overall group preference for residential spaces is shown in Figure 9. The bedroom, living–dining room, and kitchen received the highest combined weights, accounting for approximately 48%, indicating that participants generally placed greater importance on spaces related to daily living and private rest. This was followed by the powder room and toilet, with a combined weight of about 25%, while storage, balcony, and entrance hall spaces received relatively lower weights, accounting for approximately 18%. The Friedman test indicated that the differences in importance rankings among the nine residential functional spaces were statistically significant, $\chi^2(8) = 94.629$, $p < 0.001$. The relatively high Kendall's $W = 0.591$ further suggests that participants showed a consistent overall judgment regarding which spaces were more important. Although the degree of importance assigned to each functional space varied across individuals, there was still a broadly shared ranking order. These results help to clarify the functional needs of the sample and provide contextual support for interpreting subsequent differences in floor plan preferences.

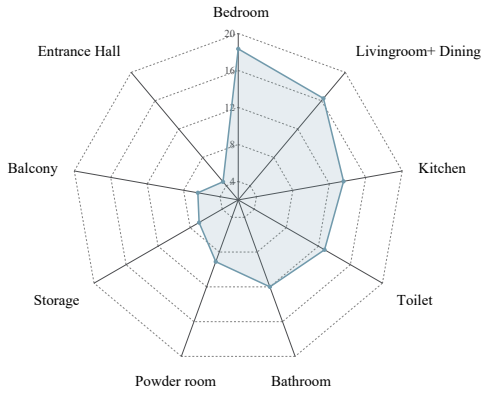


Figure 9. Group-Level Functional Priorities of Residential Spaces Based on Borda Scores.

4.2. Reliability of Subjective Ratings Under 2D and VR Conditions

Considering that the RSSQ includes three dimensions—Privacy, Comfort, and Functionality—Cronbach's α, McDonald's ω, and average variance extracted (AVE) were calculated for each dimension at three data levels, namely ALL (2D + VR), 2D, and VR, and

their 95% confidence intervals were estimated using bootstrap resampling. The results are presented in Table 7. Overall, the RSSQ showed a certain degree of structural stability under different presentation conditions, although clear differences remained across dimensions.

Table 7. Reliability Results of RSSQ Dimensions under the ALL, 2D, and VR Conditions.

RSSQ Dimension	Items	Data	*n*	*a*	*ω*	*AVE*
Privacy	Q9, Q12, Q13	All	320	0.584	0.755	0.594
		2D	160	0.509	0.716	0.557
		VR	160	0.535	0.758	0.603
Comfort	Q1–Q4, Q10, Q11	All	320	0.725	0.733	0.321
		2D	160	0.646	0.663	0.258
		VR	160	0.770	0.775	0.372
Functionality	Q5–Q8	All	320	0.598	0.619	0.298
		2D	160	0.444	0.455	0.183
		VR	160	0.702	0.734	0.422

The results indicate that the Privacy dimension showed relatively stable internal consistency and convergent validity across all three data levels. Under the ALL, 2D, and VR conditions, the ω values were 0.755, 0.716, and 0.758, respectively, while the corresponding AVE values were 0.594, 0.557, and 0.603. These results suggest that the items within this dimension had good internal convergence and remained highly stable across different presentation modes. In contrast, the Comfort dimension showed generally acceptable internal consistency overall (ω = 0.663–0.775), but its AVE values were relatively low (0.258–0.372), indicating that this dimension is more likely composed of multiple sub-attributes, such as area, daylighting, and orientation, and is therefore better understood as a composite evaluative dimension rather than a single latent construct.

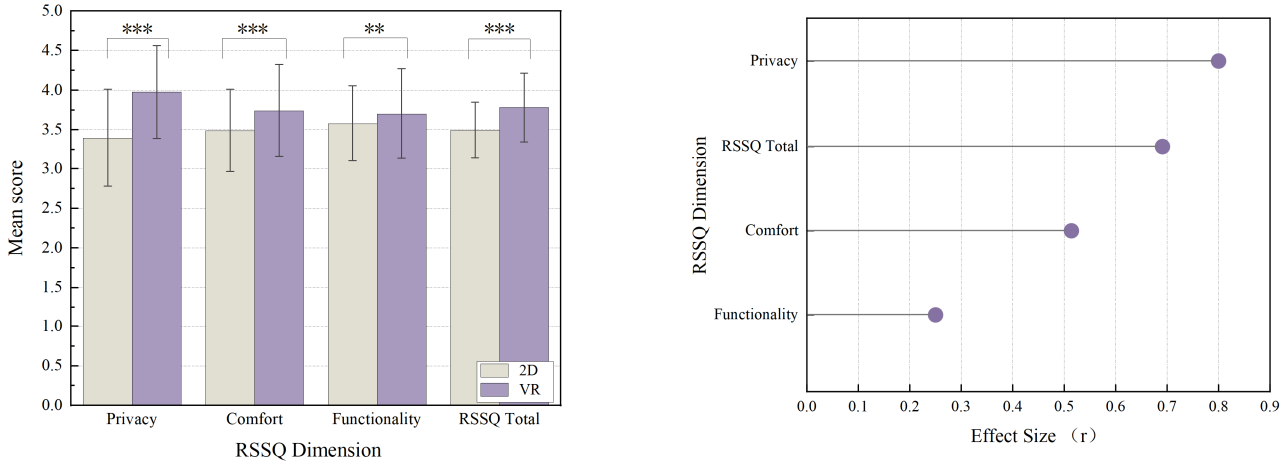
The Functionality dimension showed the most pronounced differences across presentation media. Under the 2D condition, its internal consistency was relatively weak (α = 0.444, ω = 0.455), whereas under the VR condition it improved substantially (α = 0.702, ω = 0.734), with AVE also increasing from 0.183 to 0.422. Although its convergent validity still did not reach the ideal threshold, this change suggests that immersive presentation may improve participants' consistency in understanding and evaluating functionality-related items.

Overall, the Privacy dimension remained relatively stable across different presentation conditions, whereas the Comfort and especially the Functionality dimensions were more sensitive to the presentation medium. This indicates that the RSSQ provided a basically acceptable measurement foundation in this study and also supports the subsequent comparison of subjective evaluation differences between the 2D and VR conditions.

4.3. RQ1: Differences in Dimensional Scores and Total Scores Between the 2D and VR Conditions

To address RQ1, this study used the Wilcoxon signed-rank test to compare differences in the three dimensions—Privacy, Comfort, and Functionality—as well as the total RSSQ score between the 2D and VR conditions. As shown in Figure 10a, the mean scores of all four indicators were higher under the VR condition than under the 2D condition. Statistical testing further indicated that all four measures showed significant differences between the two experimental environments. The difference in Privacy was the most pronounced ($W = 227.0$, $p < 0.001$) and also showed the largest increase in mean score ($\Delta M = 0.583$). Comfort likewise showed a significant difference ($W = 1667.0$, $p < 0.001$, $\Delta M = 0.251$). Although the increase in Functionality was relatively smaller, it still reached statistical significance ($W = 2772.5$, $p = 0.00158$, $\Delta M = 0.122$). The total RSSQ score was also higher in the virtual environment than in the 2D condition ($W = 1037.5$, $p < 0.001$, $\Delta M = 0.288$).

These results indicate that, compared with the traditional 2D presentation, the immersive VR environment elicited higher subjective evaluations of residential space. Moreover, the advantage of VR was not limited to the overall score but was also reflected across different perceptual dimensions.



(**a**) (**b**)

Figure 10. Comparison of RSSQ scores and effect sizes between the 2D and VR conditions: (**a**) mean scores by dimension; (**b**) effect sizes (*r*).

Beyond significance testing, effect sizes were further calculated to evaluate the magnitude of the impact of the VR condition relative to the 2D condition across different evaluation dimensions, as shown in Figure 10b. The effect sizes followed the order of Privacy ($r = 0.880$) > RSSQ total ($r = 0.691$) > Comfort ($r = 0.514$) > Functionality ($r = 0.250$). These results indicate that the influence of VR was not uniform across dimensions. Its advantage was mainly concentrated in Privacy, Comfort, and the overall evaluation, whereas its effect on Functionality was relatively limited. Taken together with the pattern of mean changes, these findings suggest that immersive VR was more effective in enhancing participants' perception of spatial boundaries, privacy, and overall spatial quality, while changes in presentation medium had a comparatively smaller effect on judgments of functionality.

Overall, the results for RQ1 indicate that there were statistically significant differences in the three-dimensional scores as well as the total score between the 2D and VR conditions. In the evaluation of residential spatial experience and preference, immersive VR not only provided participants with a stronger sense of representation but also more effectively amplified perceptual differences related to spatial experience.

4.4. RQ2: Differences in Floor Plan Discriminability and Preference Ranking Credibility Between the 2D and VR Conditions

To examine differences in preference identification between the two presentation conditions, this study further calculated several floor plan discriminability indicators based on each participant's total scores for the eight floor plan schemes under the two environments. These indicators included the standard deviation of ratings (SD), range, the score gap between the first- and second-ranked schemes (Top1–Top2 Gap), and the score gap between the highest- and lowest-ranked schemes (Top1–Bottom Gap). The Wilcoxon signed-rank test was then used to conduct paired comparisons between the 2D and VR conditions. Finally, Kendall's *W* was used to assess the consistency of group-level rankings under the two environments.

As shown in Table 8, all discriminability indicators were higher under the VR condition than under the 2D condition. In the immersive virtual environment, participants exhibited

larger rating differences across floor plan schemes, clearer preference hierarchies, and greater discriminability among the schemes. Wilcoxon signed-rank tests further showed that all four paired comparisons reached statistical significance (all $p < 0.05$). In addition, the effect sizes of all comparisons were above 0.60, indicating that these differences were not only statistically significant but also of considerable practical significance.

Table 8. Comparison of Floor Plan Discriminability Indicators between the 2D and VR Conditions.

Metric	2D Mean	VR Mean	W	*p*	Effect Size r
SD	4.19	5.47	31.0	0.004	0.618
Range	12.30	16.40	17.0	0.003	0.703
Top1–Top2 Gap	2.80	4.50	21.5	0.016	0.601
Top1–Bottom Gap	12.30	16.40	17.0	0.003	0.703

In terms of preference ranking consistency, Kendall's *W* reached statistical significance under both conditions, as shown in Table 9, indicating that the participant group exhibited a relatively stable consensus in ranking the floor plans under both the 2D and VR environments. Specifically, Kendall's *W* was 0.560 under the 2D condition and 0.590 under the VR condition, with the latter being slightly higher. This suggests that the immersive virtual environment had a certain advantage in improving the consistency of group preference rankings. Combined with the Top1–Top2 Gap results, it can be further inferred that the virtual environment not only enhanced the discriminability among floor plans but also contributed to the formation of clearer group-level preference rankings.

Table 9. Comparison of Group-Level Preference Ranking Consistency between the 2D and VR Conditions.

Env.	Participant	Plans	Kendall's W	Chi-Square	*p*
2D	20	8	0.560	78.35	<0.001
VR	20	8	0.590	82.55	<0.001

Accordingly, RQ2 was supported. Compared with the traditional 2D condition, the VR condition significantly enhanced participants' ability to discriminate among different floor plan schemes and showed slightly higher-ranking consistency at the group level. Therefore, compared with the 2D condition, the virtual environment demonstrated a stronger discriminative advantage in supporting expressed floor plan preference identification in residential design evaluation.

4.5. RQ3: Consistency Between Subjective Floor Plan Preference Rankings and PCA-Based Physical Framework Scores

Taken together, the results of Sections 4.3 and 4.4 indicate that subjective ratings under the VR condition showed greater discriminability and clearer preference rankings. Therefore, this section further uses the floor plan ranking obtained in the VR environment as the subjective evaluation result and compares it with the floor plan ranking derived from the PCA-based analysis in Section 3.2. To assess the consistency between the two, Spearman's rank correlation, Kendall's tau, and the mean absolute rank difference were employed.

The results indicate that the consistency between the subjective ranking obtained under the VR condition and the PCA-based ranking was weak. Spearman's $\rho = 0.071$ and Kendall's $\tau = 0.071$, neither of which reached statistical significance ($p > 0.05$), while the mean absolute rank difference was 2.50. These findings suggest that even under the more immersive VR condition, which was better able to stimulate subjective judgment, the

floor plan preference ranking formed by users still did not show clear consistency with the PCA-based ranking derived from quantified physical attributes.

Overall, the results for RQ3 indicate that only limited consistency existed between the floor plan preferences derived from subjective evaluations and the ranking generated by the PCA-based physical framework. Residential schemes with higher scores in terms of physical attributes did not necessarily correspond to higher subjective preference. Rather, the relationship between the two was not a simple one-to-one correspondence, and clear differences remained in the judgment of floor plan priority.

4.6. Limitations

Nevertheless, several limitations of this study should be acknowledged. First, the sample size was relatively small, and the participants were mainly young adults with architecture-related backgrounds. Therefore, the external generalizability of the findings still requires further verification. Second, the research objects were mainly limited to small- and medium-sized residential units within a specific floor-area range in Fukuoka, and did not cover a broader variety of housing types, household structures, or regional differences. Accordingly, the scope of applicability remains limited. Finally, the measurement of subjective residential preference in this study was primarily based on the three dimensions of the RSSQ. Although this framework was able to respond well to the core research questions, it still may not fully capture the complexity of residential preferences in real-world housing contexts.

5. Conclusions

This study took small residential units currently on the market in Fukuoka as the research object. By integrating space syntax and principal component analysis, the privacy, comfort, and functionality of eight sample floor plans were quantitatively evaluated. Furthermore, based on RSSQ subjective evaluations collected under two experimental conditions—2D presentation and immersive VR—the study examined differences in housing preferences across presentation media and their relationship with the ranking derived from the physical framework.

The results show that, first, the Privacy, Comfort, Functionality, and total RSSQ scores under the VR condition were all significantly higher than those under the 2D condition, indicating that immersive presentation could more effectively stimulate participants' subjective perception and evaluation of residential space. Second, compared with the 2D condition, the VR condition demonstrated greater floor plan discriminability and clearer preference rankings, as participants were better able to differentiate among alternative schemes and form a more stable group-level ranking under VR. Third, the subjective ranking formed under the VR condition showed only limited consistency with the floor plan ranking derived from PCA-based physical attributes, suggesting that schemes with higher physical-attribute scores did not necessarily correspond to higher subjective preference among users.

Overall, this study shows that the quantitative evaluation of residential floor plan attributes does not have a simple one-to-one correspondence with the expressed residential floor plan. The PCA-based physical framework can provide a relatively objective analytical reference for comparing residential schemes and helps identify physical differences among floor plans from the perspectives of privacy, comfort, and functionality; however, it still cannot replace the subjective judgments formed by users on the basis of actual spatial perception. By contrast, immersive VR not only improves the sensitivity of residential evaluation but also more clearly captures young users' expressed residential floor plan preferences under simulated pre-occupancy evaluation conditions, indicating that it has

stronger expressive and discriminative advantages than the traditional 2D condition in the evaluation of unbuilt residential designs. Therefore, in the early stage of residential design, it is insufficient to rely solely on physical attributes or design experience to judge the merits of a scheme. Instead, it is more necessary to combine the quantitative analysis of residential floor plan attributes with VR-based user evaluation, so as to achieve a more comprehensive understanding of the potential strengths and weaknesses of residential schemes and to promote a shift in residential design evaluation from an approach dominated by standardized supply and designer-side judgment toward one that places greater emphasis on the needs and experiential feedback of potential users.

Future studies could further incorporate larger and more diverse participant samples, broader residential types, and different regional contexts, while also integrating behavioral data, physiological indicators, and longer-term tracking of residential experience. In addition, future work could further examine how traditional 2D drawings and immersive VR environments influence users' perception and evaluation of residential space, particularly by clarifying the role of VR's immersive, interactive, and experiential advantages in supporting the formation of spatially grounded residential preferences. These extensions would help supplement and refine the evaluation mechanism of residential design, thereby establishing a more user-responsive and practically explanatory method for understanding young users' residential preferences and supporting residential design assessment.

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Abbreviations

The following abbreviations are used in this manuscript:

AEC	Architecture, Engineering, and Construction
AVE	Average Variance Extracted
FAC1,2,3	Factor Scores of Principal Component 1,2 and 3
FAC1-1	Reversed Factor Score of Principal Component 1

LDK	Living-Dining-Kitchen
Near-PD	Near-Positive-Definite
PCA	Principal Component Analysis
PC1,2,3	Principal Component 1,2 and 3
RQ1,2,3	Research Question 1,2 and 3
RSSQ	Residential Spatial Satisfaction Questionnaire
VR	Virtual Reality

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