The Impact of Historical Street Interface Morphology on Spatial Perception: An Empirical Study Based on VR Experiments

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Abstract. In the context of urban regeneration and cultural tourism development, the quality of historical street interfaces plays a key role in shaping spatial experience and the perception of historic character. However, existing studies often examine either morphological attributes or perceptual evaluation separately, lacking controlled empirical validation. This study explores the relationship between interface morphology and spatial perception using a VR-based experimental approach. West Street in Quanzhou is reconstructed as a virtual prototype, Nine experimental scenarios were created using orthogonal design,with an additional baseline scenario (S0) of the real street condition,making a total of 10 scenarios. by manipulating four variables:D/H, façade alignment ratio, interface density, and transparency. Participants experience these scenarios in an immersive VR environment and complete questionnaire-based evaluations. Results show that As D/H increases, enclosure decreases and openness increases., with comfort peaking at moderate levels, while façade alignment ratio enhances order and continuity, interface density strongly influences perceived continuity, and transparency has the greatest impact on permeability and also improves comfort. These findings provide empirical support for optimizing interface design in historical street regeneration.

Keywords: Historical streets; street interface; interface morphology; spatial perception; virtual reality

1 Introduction

Historical districts serve as important carriers of urban cultural heritage and public activities, while streets, as the most frequently used public spaces within these districts, play a critical role in shaping both residents' daily use and tourists' experiences [1][2]. As the primary boundary system of pedestrian spaces, street interfaces determine key experiential attributes such as spatial enclosure, visual permeability, interface continuity, and informational richness [3]. In current urban regeneration practices, issues such as façade setbacks, disrupted continuity, excessive openness, and imbalanced proportions are common, which can significantly alter pedestrians' spatial perception and lead

R. Zur et al. (eds.), *Proceedings of the 2026 5th International Conference on Art Design and Digital Technology (ADDT 2026)*, Advances in Computer Science Research 131,
https://doi.org/10.2991/978-94-6239-737-8_48

to variations in street-level experience, ultimately affecting the overall quality and effectiveness of regeneration efforts. Although previous studies have made important contributions to the quantification of street morphology and the evaluation of spatial perception, real-world street environments are often influenced by multiple confounding factors, including land use, pedestrian flow, lighting conditions, and material properties, making it difficult to isolate the independent effects of interface morphological variables [4]. Therefore, it is necessary to adopt controlled VR-based experimental methods, in which street characteristics are kept consistent while systematically manipulating interface parameters, to establish a clear evidence chain linking interface morphology and spatial perception through orthogonal scenario design and statistical analysis [5][6].

2 Literature Review

2.1 Spatial Perception in Historical Districts

Research on spatial perception generally suggests that street experience can be decomposed into measurable subjective evaluation dimensions, which can be systematically linked to built environment attributes. Classic urban design studies have operationalized key qualities such as enclosure, transparency, complexity, human scale, and imageability, providing a foundational framework for subsequent "morphology–perception" research [7]. In recent years, the focus has shifted toward examining the consistency and divergence between subjective evaluations and objective environmental features, with large-scale datasets and image-based analyses used to reveal interpretable relationships between streetscape perception and environmental elements, thereby informing indicator selection and model construction [6][7]. Within the context of historical districts, spatial perception extends beyond physical form to include place atmosphere, cultural imagery, and emotional responses. Emerging studies have begun to explore how visual characteristics of historical streets influence emotional and experiential outcomes, and have highlighted the necessity and feasibility of conducting quantitative perception analysis within virtual historical streets and three-dimensional virtual environments [8].

2.2 Quantification of Historical Street Interface Morphology

Research on the quantification of historical street interface morphology mainly follows two approaches: geometric measurement based on street width, building height, and their ratios, and interface attribute measurement focusing on alignment, continuity, and visual permeability. The height-to-width ratio (D/H) represents spatial enclosure and is a classic indicator for examining enclosure–openness experience. It has been shown to have stable associations with perceived enclosure, openness, and comfort, and is well suited for controlled manipulation in simulation experiments [9][10]. The façade alignment ratio (FAR) measures the degree to which building façades align with the street boundary, reflecting the regularity and continuity of the street wall. This alignment significantly influences perceived order, boundary clarity, and spatial legibility, thereby affecting pedestrian continuity experience [1]. Interface density (ID) describes the intensity of street wall composition per unit street length, emphasizing whether boundaries are continuous and gaps are minimized. It directly corresponds to pedestrians' perception of continuity and integrity [20]. Transparency (TR) refers to the visual permeability provided by openings such as doors and windows, and is commonly used to explain differences in perceived openness, permeability, and willingness to stay. Under similar geometric conditions, variations in transparency can significantly alter subjective judgments of enclosure and openness and may generate spillover effects on comfort [13][21]. Additional indicators, such as setback ratios, opening frequency and rhythm, and ground-floor functional mix, are often incorporated to enhance explanatory power or serve as control variables [7].

2.3 Application of Virtual Technologies in Perception Studies of Historical Districts

Compared to field surveys, virtual reality (VR) offers advantages in repeatability and controllability, effectively reducing interference from land use, pedestrian flow, and lighting conditions, thereby enhancing causal inference [8]. Previous studies have used immersive VR to evaluate public acceptance of future street designs and have combined self-reported, behavioral, and physiological measures to assess the impact of different street configurations on experience [10]. Other research has employed VR across different national contexts to examine the relationship between pedestrian perception and street environments, confirming VR as an effective tool for investigating environment–perception relationships. Furthermore, deep learning frameworks integrating street-view imagery and VR interaction have been applied to measure visual walkability and contributing features, demonstrating the potential of VR for perception annotation and quantitative modeling [9][12]. In the context of historical districts, VR has been used to reconstruct historical environments and analyze their effects on tourist intentions, imagination processes, and experiential evaluation, providing a digital experimental pathway for historical street research.

Despite these advances, significant gaps remain in VR-based experimental studies of historical street interfaces. Existing research rarely employs VR as a controlled experimental platform to establish direct and testable links between interface morphology and spatial perception in immersive environments, with most evidence still relying on static image-based surveys [8][11]. There is also a lack of studies that systematically construct comparative scenarios through parametric manipulation of interface morphology while maintaining consistent historical characteristics. As a result, decision-making in regeneration practice lacks empirically validated evidence. To address this gap, this study conducts a VR-controlled experiment based on West Street in Quanzhou. Under consistent stylistic conditions, key interface variables—including D/H ratio, façade alignment ratio, interface density, and transparency—are systematically manipulated at different levels using an orthogonal design. By combining scenario ranking and one-way ANOVA, the study identifies significant influencing factors and preference patterns, providing quantifiable and verifiable design references for historical street interface regeneration [10].

3 Methodology

Quanzhou, as an important historical and cultural city in China, preserves a relatively intact traditional street pattern and regional architectural character within its historic urban area. Among these, the West Street historical district is characterized by a long development history and a high concentration of cultural heritage resources, making it both typical and representative. The district not only retains well-preserved traditional features but also contains a substantial number of historical buildings, effectively reflecting the spatial characteristics of traditional urban environments. Therefore, it is selected as the study site for quantitative analysis of historical street morphology.

In this study, a typical historical street interface in Quanzhou is first reconstructed at a 1:1 scale to create immersive VR scenarios, ensuring consistency in stylistic elements, material characteristics, and overall environmental conditions across different experimental scenes. Subsequently, while maintaining the original prototype and stylistic consistency, four key interface morphological variables—D/H, façade alignment ratio (FAR), interface density (ID), and transparency (TR)—are systematically manipulated. An orthogonal design is employed to generate ten experimental scenarios [11]. Participants experience these scenarios within a VR environment and complete questionnaire-based evaluations, with dependent variables focusing on two perception dimensions: overall spatial perception and interface perception. Finally, scenario preference ranking and one-way ANOVA are conducted to identify the significant effects of different interface morphological variables on spatial perception and to reveal preference patterns, thereby providing a quantitative basis for morphological control in historical street interface regeneration.

3.1 Research Preparation

Experimental Setup.

The VR experiment was conducted in the immersive virtual reality laboratory. The experimental platform consisted of a VR content rendering and interaction engine , a head-mounted display, and its associated interaction devices. During the experiment, the virtual scenes were rendered in real time on the workstation and transmitted to the head-mounted display via wired streaming, enabling participants to experience the environment immersively and perform spatial perception tasks.

VR Scenario Construction.

To examine the effects of historical street interface morphology on spatial perception under controlled conditions, this study employed an immersive VR-based experimental approach to construct virtual scenarios. A typical street segment from a historical street in Quanzhou was selected as the prototype and reconstructed at a 1:1 scale. While maintaining consistent historical stylistic characteristics, key interface morphological parameters were systematically manipulated to generate multiple experimental scenarios, enabling comparative testing of different morphological configurations based on the same street prototype. Field measurements were conducted using a total station, indicating that the existing condition of West Street in Quanzhou has D/H of 1.828, an average interface density of 94.6%, a façade alignment ratio of 79.7%, and a mean transparency of 21.47% (Fig. 1) [12][13].

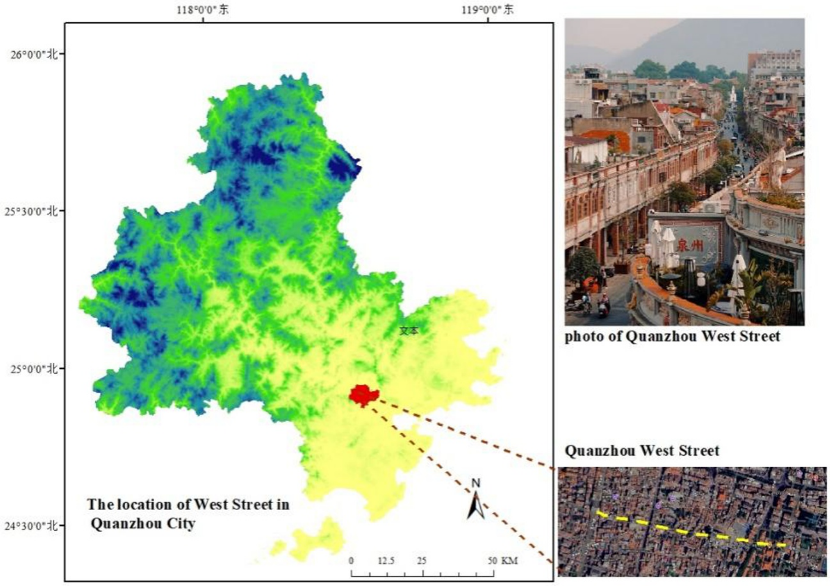

Fig. 1. Location of the research site

Participants.

A total of 152 participants were recruited to take part in the VR experiment. All participants had normal or corrected-to-normal vision and were able to complete the VR navigation and questionnaire evaluation tasks. The sample consisted of 93 females and 59 males, with ages ranging from 14 to 40 years.

Questionnaire Design.

To capture participants' psychological perceptions across different VR scenarios, a structured questionnaire was employed as the primary tool for subjective data collection. The questionnaire was designed to measure two dimensions of spatial perception: overall spatial perception and interface perception, supplemented by overall preference evaluation and scenario ranking tasks, forming a comprehensive data structure suitable for variance analysis and preference pattern identification.

The first section collected participants' demographic information, including age, gender, occupation, frequency of visiting historical districts, and prior VR experience, to characterize the sample and control for potential individual differences [14]. The second section assessed overall spatial perception, measuring participants' experience of the street environment through three psychological indicators: enclosure, openness, and comfort. The third section focused on interface perception, evaluating participants' perception of street façades through three indicators: orderliness, continuity, and permeability [15]. The fourth section addressed overall preference and scenario ranking, including overall liking, willingness to stay, and perceived stylistic harmony. Participants were also asked to select their most and least preferred scenarios after experiencing all conditions, with optional qualitative explanations(Table 1).

The questionnaire employed a 9-point Likert scale, ranging from 1 (strongly disagree) to 9 (strongly agree), with 5 indicating a neutral response. The use of a 9-point scale allows for finer discrimination among subtle differences across multiple scenarios, facilitating subsequent mean comparisons and one-way ANOVA. All items were positively worded and consistently coded to ensure clarity and reliability in statistical analysis [16].

Table 1. Description of perception indicators in two dimensions

Perceptual Dimension	Questionnaire Bipolar Adjectives	Psychological Perception Index	Description
Overall Spatial Perception	Too Enclosed — Too Open	Enclosure Degree	Variation in the sense of spatial containment and pressure
	Too Narrow — Too Spacious	Openness	Perception of spatial scale margin and width/ narrowness
	Uncomfortable — Comfortable	Comfort Level	Comprehensive evaluation of overall spatial quality
Interface Perception	Too Chaotic — Too Orderly	Sense of Order	Visual difference in interface coherence and overall order
	Too Fragmented — Too Continuous	Sense of Continuity	Degree of continuity of street wall boundaries
	Too Closed — Too Permeable	Sense of Transparency	Visual permeability of the street interface

Reliability and Validity Testing.

To ensure the measurement quality of the VR-based questionnaire and the reliability of subsequent statistical analyses, reliability and structural validity tests were conducted prior to data analysis. Reliability was assessed using Cronbach's α coefficient to evaluate the internal consistency of the scale, where values of $\alpha \geq 0.70$ are generally considered acceptable and $\alpha \geq 0.80$ indicate good reliability [17].

Prior to formal analysis, reliability and validity tests were conducted to ensure data quality and robustness.Cronbach's α coefficients were 0.897 for overall spatial perception and 0.905 for interface perception, both above 0.80, indicating excellent internal consistency.For structural validity, the KMO value was 0.774 and Bartlett's test of sphericity was statistically significant ($\chi^2 = 1332.790$, $p < 0.001$), confirming that the data were suitable for factor analysis.Subsequent exploratory factor analysis extracted two stable factors with a cumulative variance contribution rate of 67.415%. All factor loadings were greater than 0.6, and all communalities were higher than 0.6, supporting a clear and valid two-factor structure. [18] (Tables 2 and 3).

Table 2. Results of Cronbach's α reliability test

Dimension	Number of items	Cronbach's α
Overall spatial perception	6	0.897
Interface perception	6	0.905

Table 3. KMO and Bartlett Test Results

KMO measure of sampling adequacy	0.774
Bartlett's test of sphericity (χ^2)	1332.790
df	66
Significance (p-value)	<0.001

3.2 Variable System Construction

Independent Variables.

This study selects four key street interface morphological characteristics as independent variables. D/H represents the degree of spatial enclosure; the build-to-line ratio (BTL) reflects the alignment and regularity of the street interface; interface density (ID) indicates the continuity and structural integrity of the street wall; and transparency (TR) represents the degree of visual permeability. All four variables are set at three levels (Low, Medium, High), generating nine orthogonal experimental scenarios, along with one baseline scenario (S0), resulting in a total of ten scenarios (Table 4) [12]. S0 is set as the control group for comparison with the orthogonal experimental scenarios.

D/H.

D/H is defined as the ratio of street width (D) to average building height (H): Formula(1):

$$D/H = \frac{D}{H} \tag{1}$$

where D denotes the effective street width (i.e., the clear distance between the building interfaces on both sides), and H represents the average height of the street interfaces along both sides of the street segment (which can be calculated as the mean value of the left and right façade heights) [1][19][10] (Stamps, 2005).

Façade Alignment Ratio (FAR, Build-to-Line Rate).

The façade alignment ratio (FAR), also referred to as the build-to-line rate, is used to measure the degree to which building façades align with the street boundary line. It is defined as the proportion of the façade length that forms a continuous street wall along the alignment line relative to the total length of the street segment. Formula(2):

$$FAR = \frac{\sum L_{\mathrm{BTL}}}{L_{\mathrm{seg}}} \quad (2)$$

where $\sum L_{\mathrm{BTL}}$ denotes the total length of building façades that meet the build-to-line threshold (e.g., setback $\leq t$ meters) within the street segment, and L_{seg} represents the total length of the street segment corresponding to the centerline or regulatory boundary line [2].

Interface Density (ID).

Interface density (ID) is used to characterize the intensity of "information units" along the street wall boundary. It is defined as the number of identifiable interface components per unit length of the street segment, reflecting the degree of continuity and richness in interface organization. Formula(3):

$$ID = \frac{N_{\mathrm{module}}}{L_{\mathrm{seg}}} \text{(units/m)} \quad (3)$$

where N_{module} denotes the number of interface modules within the street segment (e.g., the number of storefront bays, façade subdivisions, or equal-width façade units), and L_{seg} represents the length of the street segment. This indicator can be further standardized as the number of modules per 100 meters [6][20].

Transparency Rate (TR).

The transparency rate (TR) is used to measure the degree of visual permeability of the street interface within the pedestrian eye-level zone. It is defined as the proportion of transparent openings (such as doors, windows, and display windows) relative to the total façade area. Formula(4):

$$TR = \frac{A_{\mathrm{opening}}}{A_{\mathrm{façade}}} \quad (4)$$

where A_{opening} denotes the total area of transparent openings (e.g., doors, windows, and display windows), and $A_{\mathrm{façade}}$ represents the total façade area within the same height band (typically defined as the pedestrian visual field, e.g., 0–3 m or 0–4 m) [13][21].

Table 4. Ten experimental scenarios based on orthogonal design

	D/H	FAR	ID	TR
S1	Low	Low	Low	Low
S2	Low	Medium	Medium	Medium
S3	Low	High	High	High
S4	Medium	Low	Medium	High
S5	Medium	Medium	High	Low
S6	Medium	High	Low	Medium
S7	High	Low	High	Medium
S8	High	Medium	Low	High

S9	High	High	Medium	Low
S0	Current conditions of the West Street			

Note: S1–S9 = orthogonal experimental scenarios; S0 = baseline/control scenario (real current status).

To prevent distortion of historical character resulting from morphological adjustments, this study adopts a layered modeling strategy in which the stylistic vocabulary layer is fixed and the parameter layer is adjustable. The stylistic vocabulary layer is treated as a control variable and remains unchanged, including elements such as roof and eave forms, façade materials and color schemes, window and door typologies, signage styles and scales, as well as pavement and street environmental elements. The parameter layer, as the set of experimental independent variables, involves only the modular manipulation of interface morphological parameters without altering the underlying stylistic vocabulary. Through this approach, differences among experimental scenarios are solely attributed to variations in morphological parameters rather than stylistic changes, thereby enhancing the validity of causal inference [18].

To control participants' viewing content and minimize the influence of path variability, a fixed-route automatic playback method was employed. In each scenario, the system followed a predefined path to conduct an automated virtual walkthrough lasting 60 seconds, ensuring that all participants experienced consistent viewpoints, movement speed, and information sequences across scenarios. After each playback, participants immediately completed the questionnaire evaluation for that scenario before proceeding to the next, until all scenarios had been experienced.

Dependent Variables.

The dependent variables in this study are participants' spatial perception evaluations within VR-based historical street scenarios. In the questionnaire design, spatial perception is divided into two dimensions: overall spatial perception and interface perception, comprising six psychological indicators in total Each indicator is measured using two items, resulting in a total of 12 evaluation items. All items are rated using a 9-point Likert scale, and participants' ratings for each scenario are used as input data for subsequent statistical analyses.

3.3 Research Design

Experimental Procedure.

Before the formal experiment, participants were briefed on the research objectives, VR equipment usage, and experimental procedures, and a standardized viewing height and observation mode were set. A fixed-route automatic walkthrough was employed, where participants were not required to control movement but simply observed the scenes naturally and completed evaluations after each scenario.

During the experiment, the system sequentially presented scenarios S0–S9. Each scenario was displayed using the same street segment length and camera path, with a 60-second automatic walkthrough to ensure a complete spatial impression. After each playback, participants immediately completed the 9-point Likert-scale questionnaire. To reduce fatigue effects, a 30-second rest interval was provided between scenarios [19].

Data Analysis Methods.

To examine the effects of interface morphological parameters on spatial perception in historical streets, statistical analyses were conducted using SPSS. The analysis consisted of four main stages: (1) reliability and validity testing of the questionnaire, (2) exploratory factor analysis (EFA) and construction of composite scores, (3) preference ranking analysis, and (4) significance testing and mean comparison based on analysis of variance (ANOVA) [16].

Prior to formal analysis, reliability and validity tests were conducted to ensure data quality. Reliability was assessed using Cronbach's α coefficient, while validity was evaluated using the KMO measure and Bartlett's test of sphericity. After confirming reliability and validity, the dataset was cleaned. To validate the questionnaire structure and reduce multicollinearity among indicators, an exploratory factor analysis was conducted on the 12 items. Principal component analysis was used to extract common factors, followed by Varimax rotation to examine whether the items could be grouped into the predefined two perception dimensions. When constructing composite evaluations, factor variance contribution rates were used to determine weights for calculating overall scenario scores [20].

To identify participants' intuitive preferences for different interface morphology combinations, participants were asked to select their most and least preferred scenarios after completing all experiences. The frequency and proportion of selections for each scenario were calculated to generate preference rankings. These rankings were used to cross-validate composite scores and ANOVA results, while open-ended responses were analyzed to extract preference mechanisms and typical explanations.

To test whether different interface morphological variables significantly affect spatial perception, one-way ANOVA was conducted for each psychological indicator. Specifically, scenario samples were grouped by variable levels, and mean scores for each group were calculated. Significant differences between groups were then tested to determine whether each independent variable had a statistically significant effect on the corresponding perception indicators. For variables with significant effects, mean comparisons and trend analyses were further conducted to identify the dominant influences and sensitivity of each morphological variable. This approach enables the identification of key influencing factors and public preference patterns in historical street interface perception under reliable statistical conditions.

4 Results

4.1 Overall Ranking of Experimental Scenarios

Exploratory Factor Analysis.

After completing reliability and validity tests, an exploratory factor analysis (EFA) was conducted on the 12 questionnaire items to verify whether the two-dimensional structure of "overall spatial perception–interface perception" holds, and to provide a basis for constructing composite scenario scores. Principal component analysis was used to extract factors, followed by Varimax orthogonal rotation. A factor loading threshold of >0.6 was adopted for dimension classification.

The results show that the KMO value is 0.774 and Bartlett's test of sphericity is significant ($p < 0.001$), indicating that the data are suitable for factor analysis [20]. Two factors were extracted, with a cumulative variance explained of 67.415%. All items have communalities greater than 0.6, indicating sufficient information extraction.

Factor 1 corresponds to interface perception, including orderliness, continuity, and permeability, with loadings ranging from 0.781 to 0.854. Factor 2 corresponds to overall spatial perception, including enclosure, openness, and comfort, with loadings ranging from 0.788 to 0.837. The two-factor structure is fully consistent with the predefined dimensions, indicating good structural validity of the scale. These results confirm the reliability of the measurement structure and provide a solid basis for subsequent composite score construction and difference analysis (Tables 5 and 6).

Table 5. Results of exploratory factor analysis

Name	Fac 1	Fac 2	Communality
Encl1_mean_1	0.003	0.815	0.664
Encl2_mean_1	-0.026	0.837	0.701
Open1_mean_1	0.048	0.788	0.623
Open2_mean_1	0.012	0.813	0.661
Comf1_mean_1	-0.140	0.803	0.665
Comf2_mean_1	-0.170	0.813	0.689
Order1_mean_1	0.781	0.034	0.611
Order2_mean_1	0.852	-0.021	0.726
Cont1_mean_1	0.814	-0.093	0.672
Cont2_mean_1	0.826	-0.023	0.682
Tran1_mean_1	0.854	-0.098	0.739
Tran2_mean_1	0.809	-0.058	0.657

Table 6. Variance explained in factor analysis

Factor Number	Initial Eigenvalue	Variance Explained %	Cumulative %	Rotated SS Loadings	Variance Explained %	Cumulative % (Rotated)
1	4.491	37.427%	37.427%	4.115	34.295%	34.295%
2	3.599	29.988%	67.415%	3.974	33.120%	67.415%

Composite Scores and Ranking of Scenarios.

Based on the results of the exploratory factor analysis confirming the two-dimensional structure of interface perception and overall spatial perception, composite scenario scores were constructed to enable a comprehensive comparison of different interface morphology combinations. Following the approach of using factor variance contribution rates as weights, the rotated variance explained was adopted to determine the weighting coefficients: 34.295% for the interface perception factor and 33.120% for the overall spatial perception factor, with a cumulative explained variance of 67.415%.

Based on the composite scores, scenarios S1–S9 were ranked (Table 7). The results show that the top three scenarios are S8 (0.57), S9 (0.46), and S7 (0.43), indicating higher overall spatial and interface perception performance. In contrast, the lowest-scoring scenario is S1 (−1.34), followed by S2 (−0.58). By linking the ranking results to the combinations of independent variables (see Table 10), it can be observed that high-scoring scenarios generally exhibit a combination of relatively high enclosure (D/H) and at least one interface attribute—transparency (TR), interface density (ID), or façade alignment (FAR)—at medium to high levels. In contrast, the scenario with all variables at low levels (S1) shows significantly lower overall evaluation (Table 8). These findings suggest that, under consistent historical stylistic conditions, coordinated adjustments of key interface morphological parameters can effectively enhance public evaluations of historical street spatial quality, and provide a reference baseline for subsequent difference testing and trend analysis [21].

Table 7. Ranking of composite scenario scores

Rank	Scene	FAC1	FAC2	Score
1	S8	1.21	-0.09	0.57
2	S9	0.80	0.10	0.46
3	S7	1.01	-0.18	0.43
4	S4	0.28	0.05	0.17
5	S3	-1.11	1.44	0.14
6	S6	0.03	0.16	0.09
7	S5	-0.19	0.32	0.06
8	S2	-1.02	-0.12	-0.58
9	S1	-1.01	-1.68	-1.34

Table 8. Independent interface morphological variables of the scenarios

Rank	Scene	Score	D/H_level	FAR_level	ID_level	TR_level
1	S8	0.57	H	M	L	H
2	S9	0.46	H	H	M	L
3	S7	0.43	H	L	H	M
4	S4	0.17	M	L	M	H
5	S3	0.14	L	H	H	H
6	S6	0.09	M	H	L	M
7	S5	0.06	M	M	H	L
8	S2	-0.58	L	M	M	M
9	S1	-1.34	L	L	L	L

4.2 Association Between Street Interface Morphological Variables and Spatial Perception

One-way ANOVA.

Since each participant provided repeated ratings across multiple scenarios, the data were aggregated by "scenario–level" before conducting the ANOVA. Accordingly, the sample size for each level group corresponds to the number of evaluation entries for scenarios within that level (i.e., n =number of participants × number of scenarios at that level).

Based on the composite scenario rankings, one-way ANOVA was performed to examine whether different levels of interface morphological variables lead to significant differences in spatial perception. Specifically, D/H level, FAR level, ID level, and TR level were used as categorical factors, and six psychological perception indicators were analyzed with mean comparisons conducted accordingly.

The results indicate that D/H has significant effects on enclosure, openness, and comfort; FAR significantly influences orderliness and continuity; ID has a significant effect on perceived continuity; and TR significantly affects permeability and comfort (Tables 9–12).

Table 9. ANOVA results for D/H levels

Dependent	L (n=438)	M (n=438)	H (n=438)	F	P
Enclosure	3.99 ± 0.76	5.02 ± 0.72	6.02 ± 0.73	827.163	0.000**
Openness	6.13 ± 0.71	5.18 ± 0.73	4.32 ± 0.73	686.691	0.000**
Comfort	4.94 ± 0.76	5.63 ± 0.74	4.88 ± 0.75	134.846	0.000**
Orderliness	5.23 ± 1.05	5.27 ± 1.02	5.15 ± 1.05	1.368	0.255
Continuity	5.07 ± 1.24	5.10 ± 1.09	5.05 ± 0.97	0.217	0.805
Transparency	4.94 ± 1.15	5.04 ± 1.18	5.06 ± 1.18	1.417	0.243

Table 10. ANOVA results for FAR levels

Dependent	L (n=438)	M (n=438)	H (n=438)	F	P
Enclosure	5.00 ± 1.10	5.05 ± 1.11	4.98 ± 1.11	0.543	0.581
Openness	5.17 ± 1.03	5.23 ± 1.04	5.21 ± 1.04	0.351	0.704
Comfort	5.14 ± 0.86	5.16 ± 0.77	5.16 ± 0.82	0.138	0.871
Orderliness	4.28 ± 0.75	5.26 ± 0.70	6.11 ± 0.74	689.982	0.000**
Continuity	4.82 ± 1.07	5.12 ± 1.09	5.28 ± 1.11	20.237	0.000**
Transparency	5.07 ± 1.18	4.96 ± 1.17	5.01 ± 1.16	0.805	0.447

Table 11. ANOVA results for ID levels

Dependent	L (n=438)	M (n=438)	H (n=438)	F	p
Enclosure	5.03 ± 1.15	5.02 ± 1.05	4.97 ± 1.12	0.326	0.722
Openness	5.20 ± 1.05	5.17 ± 1.02	5.25 ± 1.03	0.675	0.509
Comfort	5.14 ± 0.80	5.16 ± 0.89	5.16 ± 0.76	0.079	0.924
Orderliness	5.17 ± 1.05	5.25 ± 1.01	5.24 ± 1.07	0.701	0.496
Continuity	4.07 ± 0.72	5.08 ± 0.77	6.07 ± 0.73	800.394	0.000**
Transparency	5.03 ± 1.19	4.97 ± 1.19	5.04 ± 1.14	0.482	0.618

Table 12. ANOVA results for TR levels

Dependent	L (n=438)	M (n=438)	H (n=438)	F	p
Enclosure	4.99 ± 1.10	5.04 ± 1.08	5.00 ± 1.15	0.316	0.729
Openness	5.24 ± 1.00	5.22 ± 1.04	5.16 ± 1.06	0.733	0.481
Comfort	4.96 ± 0.81	5.11 ± 0.79	5.39 ± 0.80	33.058	0.000**
Orderliness	5.21 ± 1.06	5.20 ± 1.05	5.24 ± 1.03	0.129	0.879
Continuity	5.07 ± 1.20	5.04 ± 0.94	5.12 ± 1.16	0.594	0.552
Transparency	3.91 ± 0.72	4.99 ± 0.72	6.14 ± 0.76	1011.608	0.000**

Mean Comparison Analysis.

Based on the one-way ANOVA results, mean comparisons of psychological perception indicators across different levels of independent variables were further conducted to clarify the direction and pattern of variation, and to cross-validate the composite scenario rankings. Overall, different interface morphological variables exhibit distinct "positional effects": scale-related variables (D/H) primarily influence overall spatial perception, while interface attribute variables (FAR, ID, TR) mainly affect interface perception, with transparency (TR) additionally showing a spillover effect on comfort [19].

Effects of D/H on Overall Spatial Perception.

D/H has significant effects on enclosure, openness, and comfort. Enclosure increases significantly as D/H decreases (i.e., stronger enclosure), while openness decreases correspondingly, indicating that variations in the D/H reshape spatial boundary perception. Comfort exhibits an "optimal mid-range" pattern, with the highest values observed at medium enclosure levels, and lower values at both low and high extremes. This suggests that spatial scale in historical streets does not follow a monotonic relationship, but instead presents an optimal enclosure threshold. Excessively low enclosure may result in blurred boundaries and spatial looseness, whereas excessively high enclosure may induce a sense of oppression, thereby reducing comfort [22].

Effects of FAR on Interface Order and Continuity.

FAR has a significant impact on perceived order and continuity. Mean comparisons indicate that order increases significantly as FAR rises from low to high levels, suggesting that higher alignment enhances the perception of façade regularity. Continuity also shows an increasing trend, indicating that improved alignment strengthens the perceived coherence of the street wall. In contrast, FAR has no significant effects on enclosure, openness, or comfort, implying that its primary influence lies in visual perception of interface order and boundary continuity [23][24].

Effects of ID on Perceived Continuity.

ID shows the most concentrated and pronounced effect on continuity. Mean comparisons reveal that perceived continuity increases significantly with higher interface density, indicating that denser and more complete street walls enhance pedestrians' perception of continuous boundaries. This finding is consistent with the theoretical assumption that interface density reflects the structural integrity of the street wall, and aligns with the characteristics observed in high-scoring scenarios.

Effects of TR on Permeability and Comfort.

TR has significant effects on both permeability and comfort. Perceived permeability increases monotonically as TR rises, indicating that higher visual openness directly enhances the perception of interface permeability. Comfort also increases with higher TR, suggesting that improvements in visual permeability not only enhance interface experience but also generate positive spillover effects on overall spatial comfort under consistent stylistic conditions [25]. Combined with the composite scenario rankings, it can be inferred that scenarios with higher TR, when paired with appropriate enclosure or interface order, are more likely to achieve higher overall evaluations.

5 Conclusions and Planning Implications

5.1 Conclusions

The spatial experience of historical streets exhibits an "optimal mid-range" threshold rather than a linear relationship. The results show that variations in D/H significantly reshape enclosure and openness, with enclosure increasing and openness decreasing as

D/H changes. However, comfort does not vary linearly with enclosure; instead, it peaks at moderate levels, demonstrating a threshold effect. This indicates that street scale control in historical street regeneration should aim for an appropriate range rather than extreme values, balancing boundary clarity and pedestrian comfort [26].

Interface attributes exhibit cross-dimensional spillover effects, where transparency not only enhances perceived permeability but also improves overall comfort. TR shows the strongest influence on permeability and a consistent gradient increase, while also significantly improving comfort. This suggests that optimizing visual permeability can simultaneously enhance both interface experience and overall spatial quality.

Public preference reflects a pattern of "combinational trade-offs" rather than simple maximization of all variables. High-ranking scenarios do not correspond to all variables at high levels, but rather to coordinated combinations where one or two interface attributes (FAR, ID, TR) are at medium to high levels under appropriate enclosure conditions. In contrast, scenarios with uniformly low levels receive the lowest evaluations. This indicates that interface optimization should follow a strategy of prioritizing key variables and achieving balanced combinations rather than uniformly increasing all parameters.

5.2 Planning and Design Implications for Historical District Regeneration

Priority should be given to establishing an "optimal enclosure range" for spatial scale control. The findings indicate that enclosure and openness vary significantly with D/H, while comfort peaks at moderate levels. This suggests that regeneration design should avoid both overly open and overly enclosed extremes. At the planning level, D/H can serve as a diagnostic indicator: for low-enclosure streets, boundary clarity can be enhanced through improved façade alignment and interface density; for high-enclosure streets, pressure can be mitigated through increased transparency and refined ground-level design.

Façade alignment and interface density should be used to shape street wall order and continuity, enhancing the legibility of historical street boundaries. FAR and ID significantly influence order and continuity, highlighting the importance of aligned and continuous street walls. These variables can be translated into design control guidelines, regulating setbacks and discontinuities to reduce large gaps while maintaining variation through detailed façade articulation [27].

Transparency optimization represents a low-cost, high-impact strategy for interface improvement. TR has the strongest effect on permeability and also improves comfort, suggesting that enhancing ground-level openness and visibility can significantly improve user experience without altering stylistic vocabulary.

Finally, a parametric and iterative evaluation framework for street regeneration is recommended. This study demonstrates that VR-based controlled experiments and statistical analysis can effectively identify key variables and their optimal levels under consistent stylistic conditions [28]. Variables such as D/H, FAR, ID, and TR can be integrated into a "diagnosis–design–evaluation–optimization" workflow, improving the measurability, interpretability, and operability of historical district regeneration [29][30].

Acknowledgment

Project source: Huizhou Philosophy and Social Sciences Planning Project 'Research on the Development of Digital Virtual Exhibition Hall of Intangible Cultural Heritage around the Two Mountains in Huizhou' (2025ZX138)

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