HOKKAIDO UNIVERSITY

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A Machine Learning–Driven Study of the Impact of Pedestrian-View Street Spatial Form on Aesthetic Judgements: Commonalities and Differences in Judgements between Local and Non-Local Visitors and Their Implications for Urban Design

— A Case Study of a Tourist Pedestrian District in Luoyang, China

歩行者視点の街路空間形態が美的判断に与える影響に関する機械学習を用いた研究：地元訪問者と非地元訪問者の判断の共通点と相違点、および都市設計への示唆

—— 中国・洛陽の観光歩行者地区を事例として

Xin Gao

1 Introduction

Against the backdrop of accelerating globalisation and post-industrial urban development, urban regeneration has emerged as a critical pathway for achieving sustainable transformation. Within this context, ageing streetscapes with rich historical layers and distinctive spatial textures are being rediscovered as valuable urban assets. A key challenge, therefore, lies in how to revitalise these spaces through tourism-driven regeneration initiatives that retain local identity and cultural heritage, while simultaneously reconfiguring them to enhance aesthetic experience. This has become an urgent agenda in contemporary urban design and policy discourse.

Firstly, the prevailing approach to urban regeneration has gradually shifted from the linear ‘demolish-and-rebuild’ paradigm to one centred on ‘renewal and transformation’—a model that prioritises spatial continuity and adaptive reuse. This approach advocates for retaining the foundational spatial structure while enhancing its functionality, upgrading supporting facilities, and improving environmental quality.

Secondly, visual spatial quality has emerged as a critical aesthetic dimension in contemporary urban design and regeneration. Incorporating users’ aesthetic evaluations into the decision-making logic of street space reconstruction not only enhances the overall urban image and spatial appeal but also contributes to the dual goals of social sustainability and environmental aesthetics.

Finally, in tourism-oriented pedestrian streets, the user base typically comprises both local residents (local visitors) and a substantial number of non-local visitors. Recognising visitors as spatial users with heterogeneous perceptual structures and systematically incorporating differentiated aesthetic preferences into the design process can enhance the aesthetic adaptability of street environments. Such an approach contributes to the creation of more inclusive and perceptually engaging urban tourism

settings.

Based on the above background, this study proposes two main research objectives:1) The core content lies in establishing a system of measurement indicators for street spatial form and aesthetic judgement, in order to explore and apply the logical relationship between the two in local and non-local visitors(as shown in **Figure 1-1**). 2) Using the system to evaluate the research site for further regulations (as shown in **Figure 1-2**).

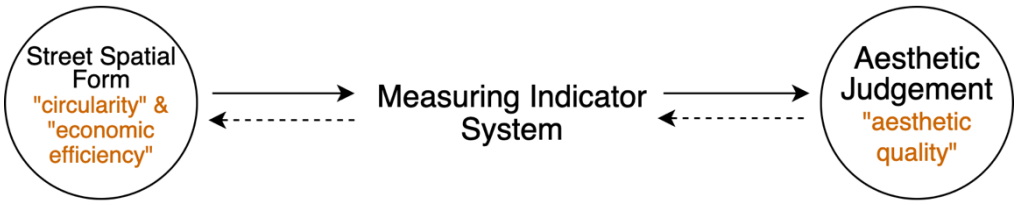

Figure 1-1. A Measuring Indicator System for Aesthetic Judgement of Urban Spatial Form for Urban Renewal (Objective 1).

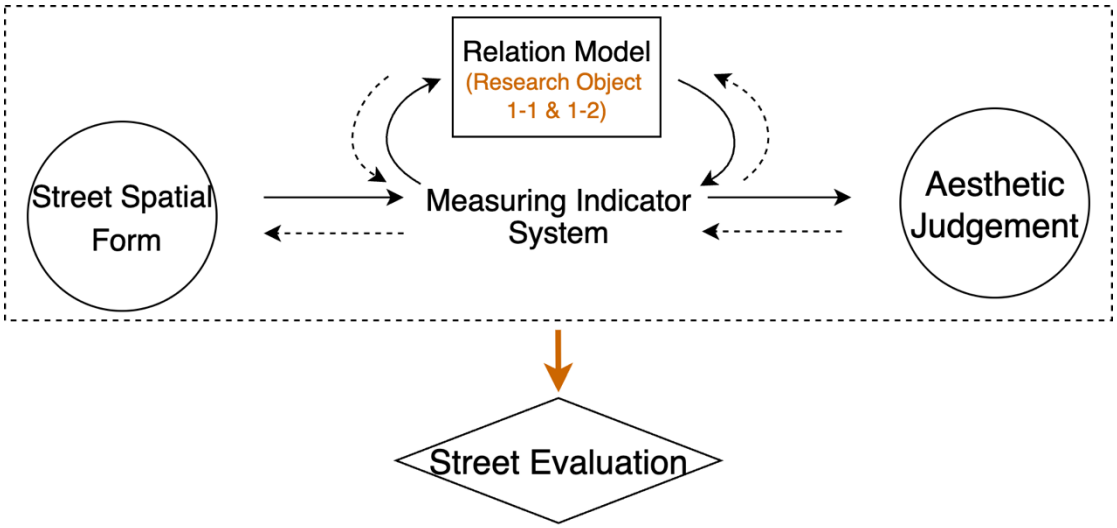

Figure 1-2. The Progress of Street Aesthetic Evaluation of the Street Site to Regeneration (Objective 2).

In addition, to achieve the research objectives more effectively, it is necessary to pursue further refinement and expansion at the methodological level. The development of more

scientifically grounded and practically applicable research methods, therefore, constitutes an indispensable component of this study.

2 Literature Review

This chapter presents the literature review of the study and is structured around three key components: the definition of relevant concepts, a review of the current state of research, and the identification of theoretical gaps and unresolved issues.

This chapter focuses on several core concepts central to this study, namely Street Spatial Form, General Conceptual Meaning of Aesthetic, and Key Related Concepts of Aesthetic Perception, Aesthetic Judgment, and Aesthetic Experience. Furthermore, Local Visitor and Non-local Visitor.

About the current research review, mainly about the perception of the urban environment and urban spatial form (street environment and visual perception; urban form and perception), cognitive and perceptual aesthetics, indicators for spatial form, and previous research methods.

Building upon the literature review and aligning with the research objectives outlined in Chapter 1, further identify the existing gaps and limitations in previous studies. Specifically, 1) Limitations of the top-down value orientation in urban planning and design. 2) Gaps related to spatial form indicators. Current studies on spatial form still lack a systematic indicator framework, and most have overlooked the understanding and analysis of spatial form from a pedestrian perspective. 3) Gaps in studies on the relationship between spatial form and aesthetic judgment. Current research generally lacks attention to the aesthetic value of spatial form, as well as to the differences between local and non-local groups. 4) Methodological limitations in studies concerning spatial morphology and aesthetic perception.

Finally, from an academic perspective, the research questions of this study are further specified across several dimensions.

1) From a theoretical perspective, it is necessary to further clarify the conceptual connotation of street spatial form from a pedestrian viewpoint and, on this basis, to establish a corresponding system of indicators. This aims to develop a new paradigm for evaluating street spatial form and urban aesthetic perception grounded in a bottom-up planning approach.

2) To what extent does spatial form exert an independent aesthetic influence, and is there an identifiable interaction mechanism between spatial form and non-structural visual elements in shaping visitors' aesthetic evaluations?

3) Do specific spatial form indicators exhibit consistency or divergence in aesthetic

evaluations between local and non-local visitors, and what does this reveal about cross-group aesthetic commonalities?

4) How can more scientific and rigorous technical methods be employed to effectively measure and evaluate street spatial form and street aesthetic perception?

3 Theoretical Section

This chapter outlines the core theoretical foundations of the study from four key perspectives. 1) outlining the study's overarching conceptual framework and the foundational perspective through which urban spatial form is interpreted. 2) focusing on the development and feasibility of spatial and aesthetic indicators. 3) reflecting on practical issues encountered in real-world street regeneration and providing theoretical responses to these challenges.

Firstly, this study advocates for a bottom-up approach grounded in the pedestrian perspective to construct an evaluative framework for street spatial form that reflects authentic aesthetic judgments. The pedestrian perspective emphasises a two-dimensional spatial mapping enriched with perspective effects, reflecting the subjective visual perception of the human visual system toward street environments.

Secondly, when constructing indicators of street spatial form from a pedestrian perspective, it is essential to consider the spatial form as it is genuinely perceived by pedestrians within the street environment. Based on principles of pedestrian visual perception, indicators of spatial form from a pedestrian viewpoint should first incorporate spatial features that can be directly observed. These features are then further transformed on the basis of relevant theoretical frameworks, leading to the generation of new indicators that reflect pedestrian visual characteristics through a three-step process. Therefore, based on these three categories, five key indicators of street spatial form have been developed: the proportion of sky (PS), the proportion of vertical elements (PV), and the proportion of ground (PG) within the visual frame; the ratio of ground to vertical elements (G/V); and spatial depth (D).

Drawing on the social attributes of spatial form, theories of direct perception, perceptual efficiency, and neuropsychology, this study establishes the feasibility of spatial form as a subject of aesthetic perception, while also identifying the similarities and differences between spatial-form-based aesthetic perception and aesthetic perception in actual environments.

Finally, this study introduces a dual-scale aesthetic evaluation framework: the Street-Level Aesthetic Value (SAV), which assesses the visual coherence, structural integrity, and aesthetic quality at the overall street scale; and the Point-Wise Aesthetic Value (PAV), which focuses on the visual details and spatial quality of specific nodes. Together, SAV and PAV establish a framework for coordinated partial–overall aesthetic

regulation, allowing for the fine-grained assessment of localised interventions while safeguarding the continuity and unity of the broader urban streetscape. This multi-scalar approach provides both theoretical grounding and methodological support for integrated street design in the context of urban renewal.

4 Site Selection and Methodology

The study adopts an integrated methodology that combines quantitative and qualitative approaches. On the one hand, qualitative analysis is used to explore the underlying psychological mechanisms and perceptual logics that link spatial form to aesthetic responses. On the other hand, the relationship between street spatial form elements and pedestrian aesthetic judgments is modelled quantitatively, including analysis of variable trends and tests of whether spatial form operates independently or in conjunction with other landscape features in shaping aesthetic evaluations. This dual approach ensures that the study's conclusions are not only statistically robust but also generalisable across contexts.

Accordingly, this section outlines the relevant theoretical foundations and methodological strategies employed in the study. It introduces the development of a process model and quantifiable index system for evaluating the aesthetic quality of street spatial form, with a particular emphasis on ensuring that the model possesses both operability and practical value in real-world urban design contexts. The following sub-sections will elaborate on each of these components in detail.

1) introduces the key technical theories underlying this study's methodology, focusing on machine learning. This part presents the primary machine learning models employed, with particular emphasis on the fundamentals of Convolutional Neural Networks (CNNs) and semantic segmentation models, discussing their technical advantages and suitability for data collection, feature extraction, and automated classification of street spatial form.

2) illustrates the feasibility of using beauty rating as a visual aesthetic measure.

3) outlines the overall research design and approach (Experiment 1 and Experiment 2).

4) describes the basic characteristics of the selected study sites.

5) details the data collection methods, including the capture of streetscape videos and the construction of an image database, the collection of spatial form indicators(semantic segmentation of street spatial elements based on the ViT-Adapter Model and ADE20K dataset, measurement of street spatial form Indicators based on the MiDaS DPT Model, (see **Figure 4-1(a)** to **4-1(b)**), the selection of experimental samples (original street view photo and sketch, (see **Figure 4-1(a)** and **4-1(d)**), and the strategy for generating outline-sketch diagrams of street spatial forms used in the experiments.

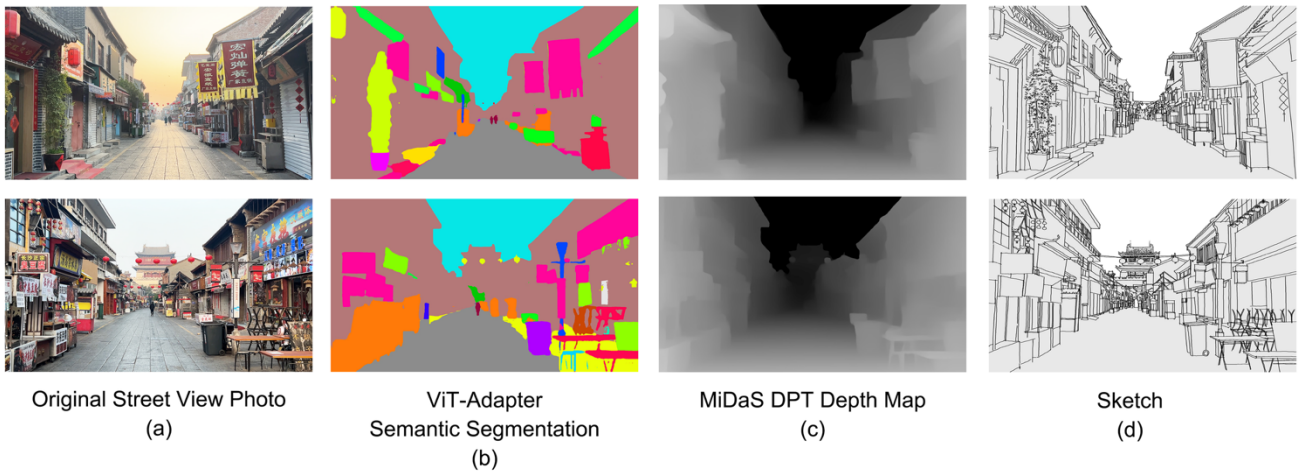

Figure 4-1. Image Preparation, Processing, and Analysis: (a) On-site street photograph, (b) Visualisation of semantic segmentation results, (c) Visualisation of depth analysis, (d) Sketch of the street's spatial form.

6) presents the questionnaire survey, covering investigations into the influence of street spatial form and real streetscapes on pedestrian aesthetic judgments, as well as the impact of spatial form indicators on the aesthetic evaluations of both local and non-local visitors.

7) describes the data analysis procedures, including linear analysis, fitting analysis, and the prediction of pedestrian aesthetic evaluations for the study sites' streets.

8) discusses control methods designed to eliminate interference from shape features in sketch images on aesthetic judgments. This includes Experiment 1's strategy to maintain consistency in shape features expressed by sketch samples, and Experiment 2's strategy to ensure cultural homogeneity among participants.

5 Results and Discussion

This chapter provides a comprehensive synthesis of the analytical results derived from the two core experiments conducted in this study. The content is organised into three main sections.

First, presents the basic characteristics of the respondent sample, and all the samples of both experiments are available.

Second, this study reveals the independent role of spatial form in aesthetic judgement and its interaction with non-structural visual elements. These findings suggest that even when colour, materials, decorative elements and other detailed visual features are removed, the spatial form alone still conveys a high level of aesthetic value.

When the spatial form itself demonstrates a strong degree of openness, its intrinsic visual order and proportional coherence become dominant contributors to aesthetic judgement. In such cases, additional non-structural visual elements present in street view images—such as greenery, colour schemes, surface materials, and signage—may fail to enhance aesthetic qualities. Conversely, in spatially enclosed settings, the inherent aesthetic contribution of spatial form is relatively limited.

Third, consistent patterns in the aesthetic perception of spatial form among local and non-local visitors. This study reveals significant non-linear interactions among spatial form indicators in both categories of people. Rather than influencing aesthetic evaluations independently or in a purely linear manner, their effects emerge through complex multidimensional combinations.

1) The study finds that higher aesthetic scores consistently occur in configurations where D and PS exhibit a positively aligned relationship, revealing a relatively stable pattern of aesthetic preference, like shallow D and low PS, a moderate street depth (approximately 0.5–0.75) combined with a mid-level PS, and a greater depth combined with a moderately high PS (see **Figures 5-1** and **5-2**).

2) Both “low depth-high openness” and “high depth-high enclosure” spatial forms demonstrate that aesthetic experiences may be negatively affected when PS, PG, and D fall into unbalanced combinations (see **Figures 5-1** and **5-2**).

3) The study reveals that PV and G/V are statistically significantly correlated with the three primary spatial form variables—PS, PG, and D.

Fourth, the ground ratio (PG), as a key spatial variable, exerts a marked influence on the aesthetic experience of visitors from different regions. Local visitors demonstrate a high degree of consistency in their aesthetic evaluation of familiar streetscapes. Even under varying depth conditions, the spatial configurations associated with both high and low aesthetic scores tend to retain similar ground ratio characteristics. Conversely, non-local visitors' aesthetic perception appears less dependent on ground ratio. That is, under different depth conditions, the same PG may elicit entirely different aesthetic responses among non-local visitors (see **Figures 5-1** and **5-2**).

Lastly, based on the evaluation results of Street-Level Aesthetic Value (SAV) and Point-Wise Aesthetic Value (PAV), it is observed that the overall aesthetic value of street form at the street level tends to be higher than the aesthetic ratings at individual point locations.

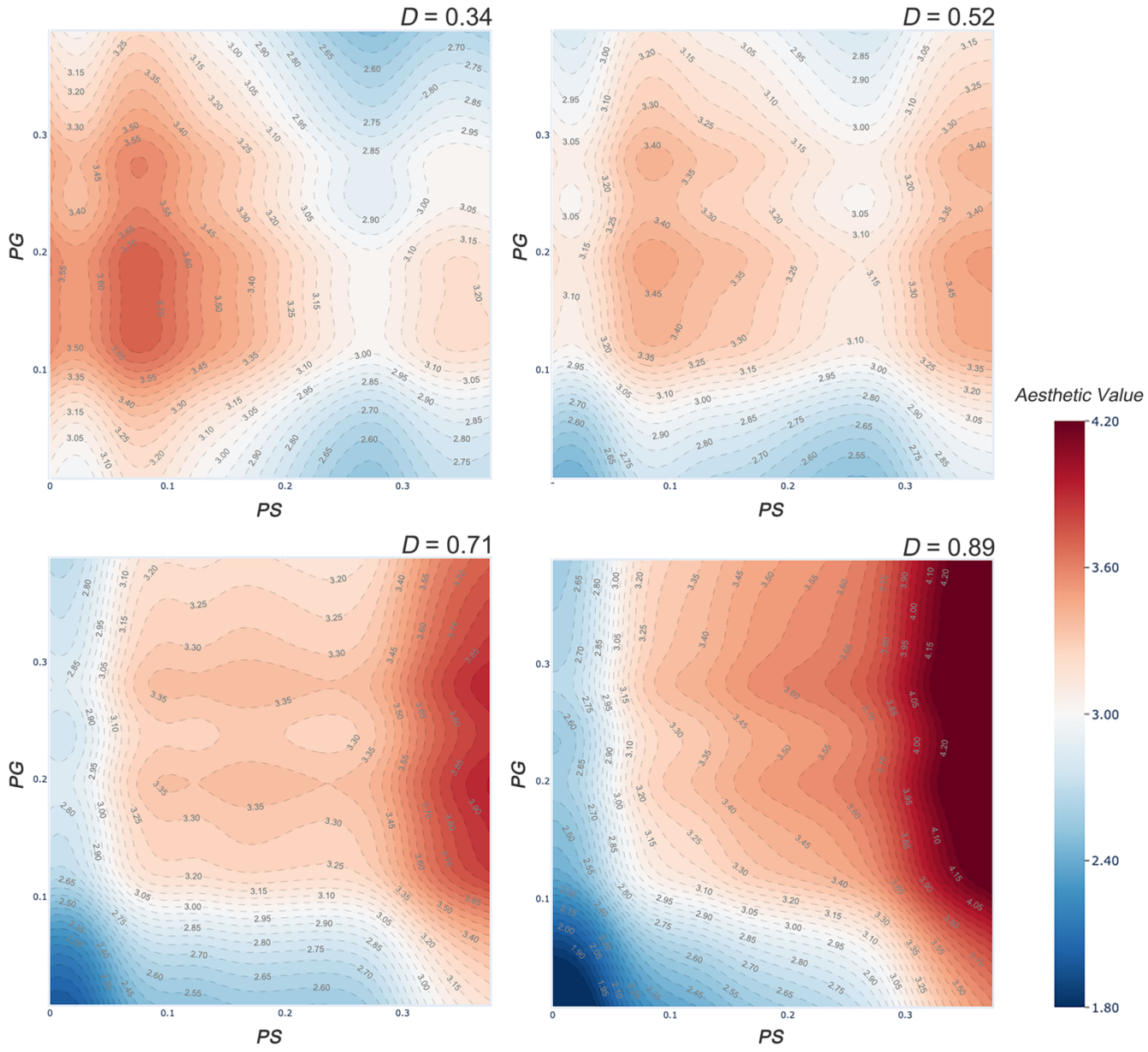

Figure 5-1. GAM Fitting Results of Spatial Form Indicators (*PS*, *PG*, *D*) and *Aesthetic Value* for Luoyang City.

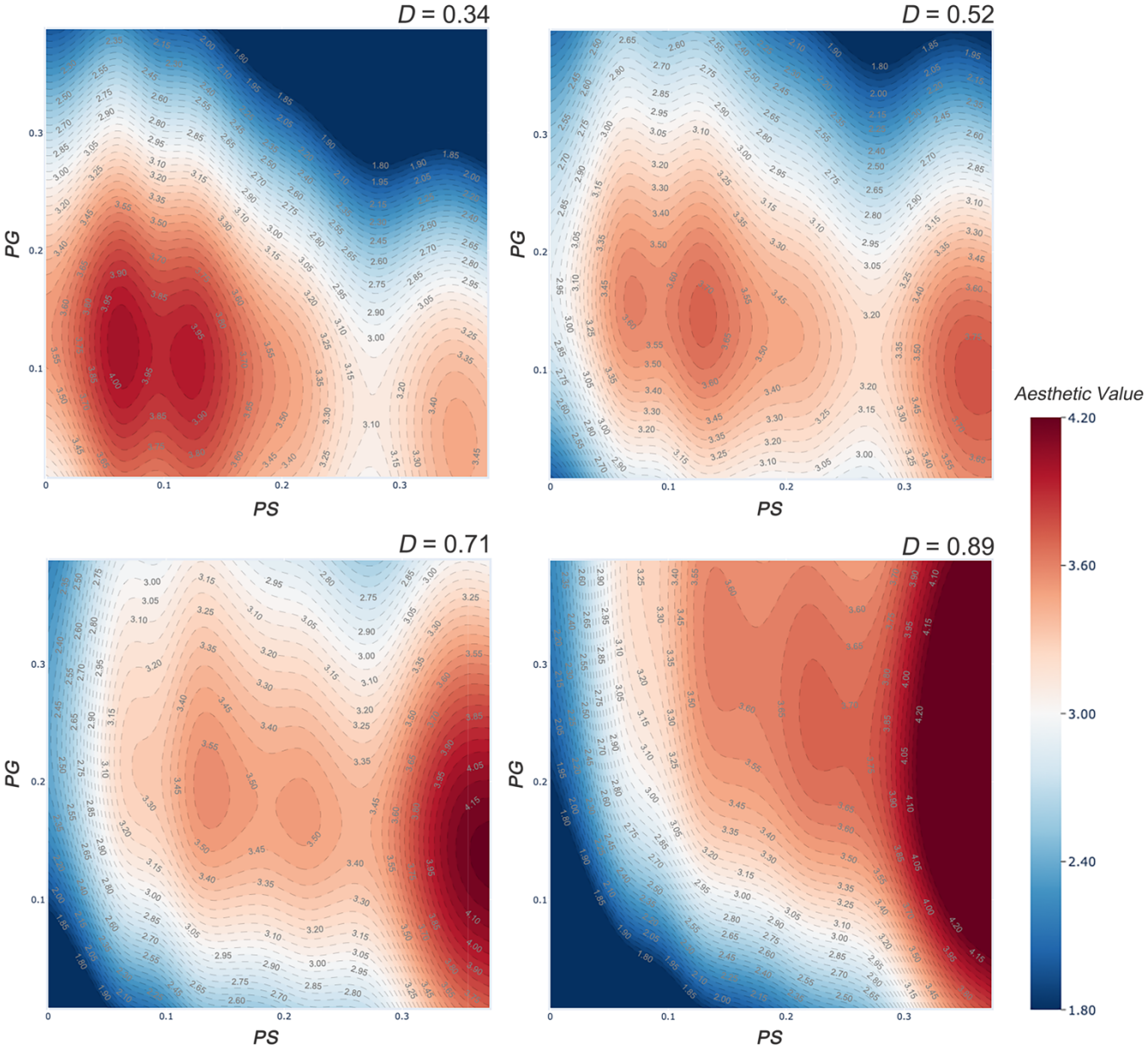

Figure 5-2. GAM Fitting Results of Spatial Form Indicators (*PS*, *PG*, *D*) and *Aesthetic Value* for Xi'an City.

Further analysis (see **Figure 5-3**) reveals that key spatial indicators at the street level—such as sky proportion (PS), ground proportion (PG), and street enclosure depth (D)—tend to fall around the mid-range of their respective value scales. According to the conclusions discussed above, a relatively balanced ratio between sky proportion and depth tends to correlate with high aesthetic evaluations. Conversely, spatial indicators at the point level display more volatility and often deviate from the spatial characteristics typically associated with high aesthetic value. As a result, many individual points receive lower aesthetic ratings, contributing to the general trend of SAV exceeding PAV.

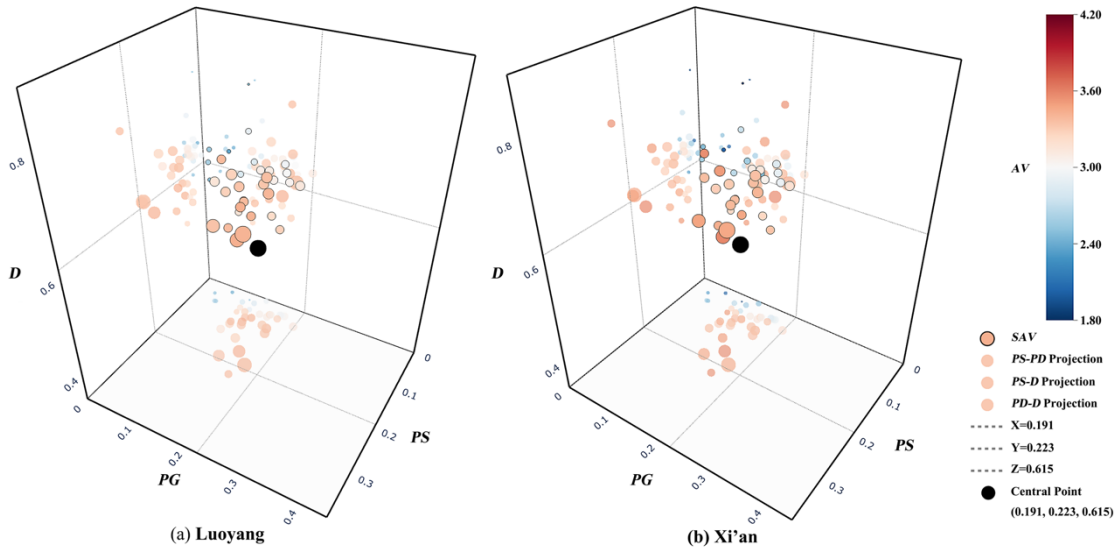

Figure 5-3. The Street-level Aesthetic Value (*SAV*) of Each Street and Its Corresponding Spatial Characteristics.

6 Conclusion

6.1 Key Findings

- The Independent Aesthetic Effect of Street Spatial Form and Its Interaction with Non-Structural Elements. Non-structural elements may diminish visitors' aesthetic perception, but can also compensate for it.
- Coexistence of Similarities and Differences in Local and Non-Local Visitors' Aesthetic Judgments of Street Spatial Form. Aesthetic perception is determined by the coordination of sky proportion, ground proportion, and depth, with ground proportion affecting local and non-local visitors differently.
- The Street-Level Aesthetic Evaluation result is normally higher than the Point-Level Aesthetic Evaluation result.

6.2 Contribution

- Theoretical Contributions

1) Research on the Visual Perception Mechanism and Aesthetic Evaluation System of Street Spatial Form Based on the Pedestrian Perspective

This study centres on the pedestrian perspective, moving beyond the conventional top-down planner-oriented approach in spatial form research by emphasising pedestrians' authentic visual perception and subjective experience. It develops an evaluation system for street spatial form that more accurately reflects actual perceptual mechanisms. By

incorporating the principles of retinal two-dimensional perspective imaging, the research systematically elucidates how three-dimensional street forms are transformed into two-dimensional projections with depth and layering effects within the pedestrian's field of view, thereby deepening the understanding of the visual perception of spatial form. This vision-based framework addresses the gap in current studies that overlook pedestrians' genuine visual logic and provides a theoretical and methodological foundation for quantifying the relationship between spatial form and aesthetic evaluation.

2) Construction of Street Spatial Form Indicators from the Pedestrian Perspective

The proposed indicators are categorised into three types: direct perception indicators (PS, PV, PG), perspective transformation indicators (D), and adapted classical indicators (G/V). These correspond respectively to elements directly perceived by the human eye, the perspective effects of three-dimensional space, and a visual reinterpretation of traditional enclosure indicators. This classification addresses the historical neglect of human visual mechanisms in spatial indicator development, effectively bridging the gap between spatial form quantification and perception-based research.

3) Rethinking the Factors Influencing Aesthetic Judgement: The Independent Value of Spatial Form and Its Interaction with Non-Structural Elements

This study first establishes that the spatial form of streetscapes exerts a significant independent influence on visitors' aesthetic judgement, and this study highlights the interactive mechanism between spatial form and non-structural visual features.

Specifically, when a street presents a "structure-dominant" form, the spatial form alone already conveys a relatively high aesthetic value. In such cases, the addition of non-structural elements does not enhance visual quality and may even detract from it. Conversely, when the street space exhibits a high proportion of vertical elements and a limited sky view, the aesthetic contribution of spatial form is diminished. Under such conditions, the introduction of non-structural visual features will ultimately enhance the overall aesthetic evaluation of the streetscape.

4) Comparison of Shared and Divergent Aesthetic Judgements Between Local and Non-Local Visitors

- Methodological Contributions

1) Integrating Spatial Form Control and Perceptual Measurement through Sketch-Based Representations

2) A Nonlinear Fitting Approach Combining Machine Learning and Generalised Additive Models (GAM)

- Practical Contributions

(Urban Regeneration Suggestion for Enhancing the Aesthetic Quality of Tourism-Oriented Pedestrian Streets through Spatial Form of the Old Urban Streets)

Against the background of heritage conservation, the decline in spatial quality in surrounding older districts and the resulting inefficiencies in land use have become increasingly prominent. From the perspective of urban renewal, this study explores pathways for improving the spatial quality of such districts, with the aim of advancing a people-centred urban design logic. On this basis, and drawing on the empirical findings of the study, urban renewal recommendations are proposed for tourism-oriented pedestrian streets in older urban areas, focusing on enhancing aesthetic quality through the optimisation of street spatial form.

Throughout the research process, the pedestrian perspective is established as one of the central focal points. Accordingly, the findings of this study are primarily applicable to relatively fine-grained urban renewal contexts in older city streets, with particular emphasis on examining the aesthetic value of street spatial form and its potential for enhancement. The conclusions not only offer urban designers design references that more closely align with pedestrians' actual perceptual experiences during planning and design processes, but also provide a degree of theoretical support for street-related management and regulatory bodies seeking to improve the aesthetic quality of street spaces. The specific implications are outlined as follows.

1) A Conservation-Oriented Strategy for Enhancing Street Aesthetic Quality

Beyond the conservation of individual heritage assets, the renewal of older urban districts should continue to be guided primarily by conservation principles, in order to avoid unnecessary waste resulting from large-scale demolition and reconstruction. By fully recognising and utilising the aesthetic value of existing spatial form, it becomes possible to maximise the use of on-site spatial resources while adhering to conservation principles, thereby effectively reducing resource waste during the renewal process.

2) Street Space Renewal Strategies Leveraging Shared and Divergent Aesthetic Perceptions of Local and Non-Local Visitors

Firstly, priority should be given to identifying, preserving, or further developing street spatial forms that are highly rated by both local and non-local visitors(A positive

correlation between street depth and sky visibility).

Specifically, the experimental results reveal that when street depth is relatively low (with a depth value around 0.4), the visible sky proportion is also low (generally below 20%). When the depth value is moderate (between 0.5 and 0.75), sky visibility typically ranges from 20% to 40%. In cases where the depth value is high (above 0.75), sky visibility tends to stabilise around 40%.

Secondly, design priorities should be aligned with the spatial aesthetic preferences of the group that demonstrates more positive evaluations.

Moreover, in cases where neither local nor non-local visitors respond positively to existing spatial configurations, non-structural spatial elements may be strategically introduced or enhanced to compensate for deficiencies in formal aesthetics.

Finally, imbalances between street depth and the proportion of visible sky within street spatial form should be minimised. For example, when street depth is moderate to low (D value between 0.5 and 0.7) and sky visibility is extremely low (below 5%) or fluctuates between 30% and 50%, aesthetic ratings tend to be low. Similarly, when the street depth is relatively high ($D > 0.7$), but sky visibility falls below 35% and ground visibility is under 10%, the overall aesthetic evaluation remains negative.

3) Enhancing Street Aesthetic Quality through the Interaction of Spatial Form and Non-Structural Elements

Firstly, optimising the spatial configuration should serve as the primary strategy for improving the overall aesthetic performance of street spaces. When spatial form plays a dominant role in aesthetic perception, its structural advantages should be fully utilised while the use of non-structural elements—such as greenery, colours, materials, and signage—should be reduced. Especially, spatial form exerts the strongest influence when the proportion of vertical interfaces in the field of view is below 65%, the ground plane occupies more than 20%, and the visible sky area falls within the range of 12% to 18%.

Furthermore, in cases where the proportion of vertical elements is excessively high or low, or where the balance between ground and sky is significantly disrupted, the overall aesthetic quality of the street space tends to deteriorate.

4) Enhancing Visitors' Aesthetic Perception through Coordinated Overall and Local Street Spatial Form

By coordinating the use of the Street-Level Aesthetic Value (SAV) and the Point-Wise Aesthetic Value (PAV) indicators, the aesthetic qualities of spatial form can be adjusted to achieve improvements in overall aesthetic perception.

6.3 Limitations of the Study

Firstly, due to constraints on participants' response time and the overall experimental procedure, only 130 street view images were selected for analysis. This relatively small sample size may have restricted the Generalised Additive Model (GAM) from fully capturing complex relationships among variables, potentially increasing the risk of overfitting and thus affecting the generalisability of the results.

Secondly, as an exploratory study, the findings remain preliminary and require further validation through larger and more diverse datasets. Extending the research to a broader range of street types and urban contexts would help enhance the external validity and robustness of the conclusions. Notably, variations in the relationship between spatial form and aesthetic perception may exist across different cities or cultural backgrounds, which raises additional challenges regarding the adaptability and transferability of the proposed model.

Finally, the viewpoint adopted in this experiment is a horizontal perspective at approximately 1.7 metres above ground level. This setting serves only as a preliminary attempt within the experimental model to explore the relationship between spatial form and aesthetic judgement, and does not fully reproduce the multiple and layered viewpoints experienced by visitors during actual visits. Consequently, this viewpoint configuration constitutes one of the limitations of the present study.