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Research on the Landscape Renewal Path of Public Spaces in Old Residential Areas Based on Eye-Tracking Technology

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Abstract

With the focus of urban construction shifting to inventory space renewal, the landscape transformation of public spaces in old residential areas has become an urgent priority. Taking the old residential neighborhoods of Fengcheng Sub-district in Jinan City as the empirical research objects, this study innovatively integrates eye-tracking physiological technology with the Kano model and Importance–Performance Analysis (IPA) to construct an objective–subjective integrated landscape evaluation framework. Subjective survey data (n = 122, determined via Yamane's finite population formula) and objective eye-tracking cognitive data (N = 30 valid participants, screened with a <80% data capture rate exclusion threshold) were collected across representative community spaces. Utilizing heatmap visual analysis, one-way ANOVA, and Gestalt/color psychology theories, the research reveals residents' explicit needs and implicit visual preferences for plant colors, water body geometries, and activity venue types. A stepwise multiple linear regression model establishes that Average Pupil Diameter (X1, positive predictor, $\beta = 0.542$, $p < 0.001$) and Fixation Count (X2, negative predictor, $\beta = -0.381$, $p = 0.006$) reliably predict Subjective Satisfaction (S) with a strong model fit ($R^2 = 0.618$, $F = 21.84$, $p < 0.001$). A multi-method convergence matrix resolves apparent metric divergences by distinguishing visual search friction from functional demand. Based on these findings, an actionable renewal framework structured as 'demand priority–space type–design method' is operationalized across three dimensions: functional repair, spatial reconstruction, and sensory optimization.

Keywords: public space of old residential areas; urban renewal; landscape evaluation; Kano–IPA model; eye-tracking experiment; physiological–psychological coupling

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1. Introduction

The process of urbanization in China has undergone a significant transition from 'incremental expansion' to 'inventory improvement' [1,2]. By the end of 2022, the urbanization rate reached 65.22%, yet a large number of old residential areas continue to face severe spatial challenges, such as facility aging, functional decline, and environmental degradation, failing to meet the evolving living needs of residents [3,4]. Although national and local policies actively promote urban renewal initiatives, a critical gap remains in the scientific, quantitative identification of residents' true preferences for public space landscape renewal [1]. Traditional renewal approaches often rely heavily on single subjective surveys or designer-led empirical judgments, which are vulnerable to cognitive bias and fail to capture implicit physiological feedback [2,5]. To address this gap, this study focuses on the

landscape renewal of public spaces in old residential areas, taking Fengcheng Sub-district in Jinan City—a representative microcosm of old urban residential dilemmas in northern China—as our empirical research object [3,6].

This research is theoretically grounded in Attention Restoration Theory (ART), which posits that natural and well-designed restorative environments can effectively alleviate mental fatigue and restore cognitive resources [7,8]. To translate these psychological restoration needs into actionable design parameters, we integrate the Kano model and Importance–Performance Analysis (IPA) [7,9]. The Kano model categorizes resident needs into hierarchical quality attributes (e.g., must-be, one-dimensional, and attractive attributes) [9,10], while IPA prioritizes landscape elements by evaluating the gap between perceived importance and current satisfaction [11]. However, purely subjective evaluations like Kano–IPA can be constrained by respondents' recall bias or mood fluctuations [5,12]. To overcome this limitation, this study incorporates eye-tracking technology to capture objective physiological and visual cognitive feedback (such as fixation patterns, gaze behavior, and pupil responses) [13,14]. By coupling physiological metrics with subjective psychological perceptions, an objective–subjective integrated evaluation system is constructed to reduce the inherent bias of single-method appraisals [5,15].

The primary objective of this study is to establish an objective–subjective integrated landscape evaluation framework for the public spaces of old residential areas, and to formulate a systematic renewal path [1]. Specifically, this research seeks to address three core research questions: (1) What are the hierarchical priorities of landscape elements in old community public spaces based on residents' subjective needs [9]? (2) How do objective visual eye-tracking indicators correlate with subjective landscape satisfaction scores [5,14]? (3) Can an integrated objective–subjective evaluation model provide a more accurate and robust decision-making basis for spatial renewal than traditional single-method approaches [2,15]? Correspondingly, we propose the following hypotheses: First, we hypothesize that there is a significant statistical correlation between physiological eye-tracking indicators (e.g., pupil diameter and fixation count) and subjective satisfaction ratings, where specific eye-tracking metrics reliably reflect visual attraction and cognitive load [13,16]. Second, we hypothesize that the integrated Kano–IPA and eye-tracking model will identify critical 'repair' elements (such as barrier-free facilities and multi-functional activity spaces) that traditional subjective surveys alone tend to misclassify or overlook [4,6].

The scientific contribution of this study is threefold [1]. Methodologically, it bridges the gap between physiological eye-tracking technology and two-dimensional psychological models (Kano–IPA), establishing a cross-validated 'physiological–psychological' joint evaluation framework [5,13]. Theoretically, it expands the application of Attention Restoration Theory (ART) to the specific micro-renewal context of old urban communities in northern China [7,8]. Practically, it delivers a structured, replicable renewal transformation framework defined as 'demand priority–space type–design method', offering data-driven decision support for urban planners, landscape architects, and community decision-makers [1].

2. Research Area and Methods

2.1. Overview of the Research Area

Laiwu District of Jinan City, serving as a core urban hub in central Shandong Province, is situated at the eastern foot of Mount Tai [3]. Benefiting from a warm temperate semi-humid monsoon climate, it offers a pleasant living environment. The district covers a total administrative area of 1739 square kilometers, governing 8 sub-districts and 7 towns, with a permanent population reaching 982,600 by the end of 2022 [3,6]. High population density coupled with diverse resident demands has intensified the urgency of public space transformation in this region [4,6].

As the core urban district of Laiwu, the public spaces within the old residential communities of Fengcheng Sub-district typically exhibit facility aging, functional monotony, and landscape degradation, representing a typical microcosm of old urban community dilemmas in northern China [1,3]. This study specifically selects the south-central residential sector of Fengcheng Sub-district—enclosed by Pengquan West Street, Fengcheng West Street, Beitan South Road, and Fengyang Road—as the empirical research area (see Figure 1) [3,6]. Built several decades ago, the communities within this boundary suffer from insufficient activity venues, damaged leisure infrastructure, and an imbalanced distribution of green spaces, resulting in a strong collective demand among residents for spatial quality improvement [4].



Figure 1. Location and Boundary Map of the Study Area in Fengcheng Sub-district, Laiwu District.

To systematically categorize the research objects, preliminary field surveys were conducted in accordance with the Overall Urban Plan of Laiwu City (2014–2030). Public spaces in Fengcheng Sub-district were classified based on their external spatial morphology, identifying a total of 32 point/area-like spatial nodes and 13 linear spaces [3]. Considering this study's primary focus on communal social interaction and landscape quality evaluation, enclosed community area-like public spaces were designated as the core research samples for in-depth investigation [6].

2.2. Integrated Objective–Subjective Methodology

To address the limitations of single-method appraisals, this research establishes an objective–subjective integrated evaluation framework combining the Kano model, Importance–Performance Analysis (IPA), and eye-tracking technology [5]. The Kano model categorizes resident demand attributes into hierarchical structures [9,10], while IPA evaluates the discrepancy between perceived importance and current satisfaction to pinpoint priority optimization zones [11]. Simultaneously, eye-tracking technology records real-time

visual focus and cognitive load, providing high-resolution physiological data to complement subjective self-reports [13,16]. This multi-method synergy enables cross-validation between physiological feedback and psychological perception, significantly enhancing the scientific reliability of landscape assessment [5,15].

2.2.1. Subjective Evaluation System Based on the Kano–IPA Model

Through extensive field surveys, expert consultations, and literature synthesis, an initial pool of evaluation indicators was established covering spatial infrastructure, functional diversity, ecological greening, and spatial safety [6]. Purely social or psychological need indicators (e.g., sense of respect or social belonging) were excluded because they cannot be directly mapped or validated via visual eye-tracking metrics [5,13]. Ultimately, a consolidated landscape evaluation index system comprising 20 key elements was formulated [10].

The subjective questionnaire consisted of two core parts: (1) demographic background (gender, age, occupation, and community usage frequency) and (2) perception evaluation [6,17]. The Kano section employed paired positive and negative functional questions on a 5-point scale, while the IPA section evaluated perceived importance and current satisfaction using a 5-point Likert scale (1 = very unimportant/unsatisfied to 5 = very important/satisfied) [9].

The target research area encompasses an urban permanent population of approximately 120,000, with the selected target communities hosting an estimated resident population (N) of 15,000 [3,18]. To scientifically determine the required questionnaire sample size (n), Yamane's sample size formula for finite populations was applied [18]:

$$n = N/[1 + N(e)^2]$$

where N = 15,000 and e = 9.0% represents the acceptable margin of error [18]. This formula yielded a minimum required sample threshold of 122 valid responses. To collect a representative sample and eliminate temporal and spatial sampling biases, an offline random intercept sampling strategy was deployed across the 32 community nodes over a continuous two-week period [17]. Surveys were conducted during both weekdays and weekends across three distinct daily time slots (morning: 8:00–10:00, afternoon: 14:00–16:00, and evening: 18:30–20:30). Exactly 122 valid questionnaires were recovered, providing a statistically sound dataset for Kano–IPA modeling [17].

2.2.2. Eye-Tracking Experimental Setup, Participant Screening, and Stimulus Standardization

Eye-tracking technology captures visual cognitive preferences by continuously tracking eye trajectories, fixation durations, and pupil dynamics [5,13]. To ensure scientific rigor, strict participant screening and stimulus standardization protocols were implemented [13,19].

For the eye-tracking experiment, a sample of 35 participants was initially recruited from the community survey pool [5,16]. Inclusion criteria required participants to have normal or corrected-to-normal vision (spherical equivalent between −6.00D and +2.00D), with no history of severe astigmatism, strabismus, cataracts, or neurological disorders [13,19]. To guarantee high data quality, a strict exclusion threshold was enforced: any recording with an eye-tracking data capture rate below 80% (attributable to excessive blinking, squinting, or head movement causing calibration drift) was discarded [12,19]. Consequently, 5 participants were excluded, yielding a final valid sample of 30 participants (16 females, 14 males; age range: 18–65 years, mean age = 41.2, SD = 14.5) [5,16]. In visual cognitive research, 30 participants represent a standard, statistically robust sample size, as high-frequency eye-trackers record continuous physiological streams (120 Hz) that rapidly reach statistical stability across heatmap and metric distributions [13,19].

The experimental stimuli consisted of 30 high-definition 3D digitally rendered landscape scenes developed from real community photographs across 5 distinct landscape categories (6 standardized scenes per category × 5 categories = 30 total stimulus scenes). To control confounding visual variables across comparative conditions, non-target environmental factors—such as camera angle (1.6 m eye level), scene scale, ambient illuminance (5000 lux virtual sky dome, matched exposure values in V-Ray), color contrast, and background buildings—were held strictly constant across paired rendering schemes.

The formal eye-tracking test was conducted in a soundproof, light-controlled laboratory to prevent ambient visual or acoustic interference (see Figure 2) [12,13]. Equipment included a Tobii Pro Fusion screen-based eye tracker (sampling rate: 120 Hz) paired with a 24-inch high-resolution display screen (1920 × 1080 pixels, 60 Hz) [20]. Participants were seated comfortably with their head resting on a fixed chin rest at a constant viewing distance of 60 cm [13,20]. A standard 9-point screen calibration was executed prior to testing. Each stimulus image was presented in randomized order for 8 s, separated by a 2 s neutral gray screen (RGB = 128, 128, 128) with a central fixation cross to reset baseline pupil diameter and eliminate visual fatigue [12,19]. Immediately following screen viewing, participants completed a brief Likert-scale satisfaction rating for each rendered scene [5,14]. The observational unit for all subsequent statistical analyses (including ANOVA and OLS regression modeling) was defined as the aggregated mean metric value per stimulus scene across all 30 valid participants (N = 30 scene observations), ensuring strict statistical independence among observational data points.



Figure 2. Experimental Setup and Protocol Flowchart for the Eye-Tracking Visual Test.

3. Data Processing and Analysis

3.1. Questionnaire Sample Capacity, Demographics, and Data Validation

3.1.1. Sample Size Calculation, Sampling Deployment, and Demographics

The target research boundary within Fengcheng Sub-district encompasses a total permanent urban population of approximately 120,000, with the selected old communities hosting an estimated target resident population (N) of 15,000 [3,18]. As detailed in Section 2.2.1, applying Yamane's finite population sample formula yielded a minimum required sample size of 122 valid responses [18]. Through offline random intercept sampling across 32 community spatial nodes over a two-week period, exactly 122 valid questionnaires were recovered [17].

Among the 122 valid respondents, females accounted for 58.2% (n = 71) and males accounted for 41.8% (n = 51), reflecting a higher daily activity level among female residents in community public spaces [6,17]. Regarding age distribution, the 30–50 age cohort formed the primary user group (39.34%), followed by the 51–70 age group (31.15%), while residents over 70 accounted for a smaller proportion (8.20%) due to survey mobility constraints [4,6]. Occupational profiles revealed that individual business owners constituted 22.13% (influenced by adjacent commercial markets), while factory workers, office employees, students, public sector staff, and farmers represented 18.85%, 14.75%, 13.93%, 13.93%, and 13.11%, respectively [3,17].

3.1.2. Reliability and Validity Testing

The questionnaire data were processed using SPSS 28.0 software [17]. To evaluate internal consistency, Cronbach's α coefficient was calculated for each scale section [17]. As detailed in Table 1, the Cronbach's α values for IPA satisfaction (0.881), IPA importance (0.877), Kano positive items (0.880), and Kano negative items (0.875) all exceeded the recommended 0.80 threshold, confirming high scale reliability [17].

Table 1. Reliability Analysis Results of the Questionnaire Scale (n = 122).

Scale Items	Number of Items	Sample Size (n)	Cronbach's α	Evaluation
IPA Analysis–Satisfaction	20	122	0.881	Excellent Reliability
IPA Analysis–Importance	20	122	0.877	Excellent Reliability
Kano Model–Positive Questions	20	122	0.880	Excellent Reliability
Kano Model–Negative Questions	20	122	0.875	Excellent Reliability

Construct validity was assessed using the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity (Table 2) [17]. KMO values for IPA satisfaction (0.886), IPA importance (0.885), Kano positive questions (0.878), and Kano negative questions (0.817) were all well above 0.80, with Bartlett's test yielding $p < 0.001$ across all scales. These metrics demonstrate excellent construct validity [17].

Table 2. Construct Validity Test Results (KMO and Bartlett's Test).

Scale Items	KMO Value	Approx. Chi-Square (χ^2)	df	*p*-Value
IPA Analysis–Satisfaction	0.886	741.523	190	<0.001
IPA Analysis–Importance	0.885	865.053	190	<0.001
Kano Model–Positive Questions	0.878	993.739	190	<0.001
Kano Model–Negative Questions	0.817	1002.733	190	<0.001

3.2. Kano–IPA Integrated Attribute Analysis and Renewal Priority

3.2.1. Kano Attribute Classification

Based on functional paired-question response matrices, the 20 landscape evaluation elements were categorized into specific Kano attribute hierarchies (Table 3 and Figure 3) [9,10]. Element 1 (Non-motor vehicle parking) was identified as a Must-be attribute (M), representing a baseline functional requirement [9]. Eight elements—including Element 5 (Night lighting), Element 6 (Sunshade/rainproof facilities), Element 8 (Barrier-free design), Element 10 (Activity space versatility), and Element 15 (Plant richness)—were categorized as One-dimensional attributes (O), where satisfaction scales linearly with performance [9,10]. Five elements—including Element 2 (Fitness venues), Element 3 (Elderly activity venues), Element 12 (Children's activity venues), and Element 20 (Cultural facilities)—were classified as Attractive attributes (A) [9,11]. Six elements were identified as Indifferent attributes (I) [9].

Table 3. Summary of Kano Model Classification for Public Space Landscape Elements.

Kano Category	Indicator Elements	Total Count
Must-be (M)	1. Non-motor vehicle parking	1
One-dimensional (O)	5. Night lighting, 6. Sunshade/rainproof facilities, 7. Outdoor infrastructure, 8. Barrier-free design, 9. Ornamental green landscape, 10. Activity space versatility, 14. Material comfort, 15. Plant richness	8
Attractive (A)	2. Fitness equipment/sports venues, 3. Elderly activity venues, 4. Water body design, 12. Children's activity venues, 20. Cultural facilities	5
Indifferent (I)	11. Identification signage, 13. Spatial division, 16. Plant color matching, 17. Lighting environment, 18. Community publicity facilities, 19. Creative space construction	6

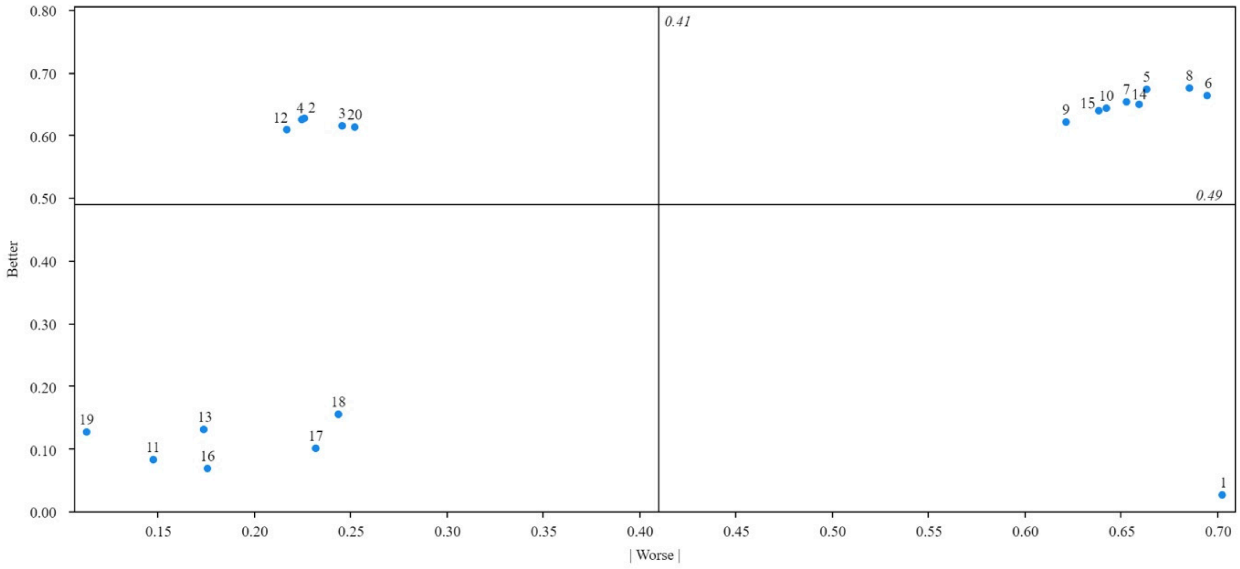


Figure 3. Better-Worse Coefficient Scatter Plot for Landscape Evaluation Elements Based on the Kano Model.

3.2.2. IPA Matrix Distribution and Sensitivity Analysis

Importance (Figure 4) and satisfaction (Figure 5) scores were plotted on a two-dimensional grid, using full-precision grand mean importance (I_mean = 4.114, SD = 0.112, SE = 0.025 across elements) and grand mean satisfaction (S_mean = 3.531, SD_element = 0.076 across element means, SD_sample = 0.098 across individual respondent scores, SE = 0.022) as coordinate crosshairs. Full-precision coordinate values confirmed quadrant placements for borderline elements near the crosshairs: Element 16 (Plant color matching: Importance = 4.120 > 4.114, Satisfaction = 3.535 > 3.531) falls in Quadrant I (Advantage Area); Element 11 (Identification signage: Importance = 4.110 < 4.114, Satisfaction = 3.538 > 3.531) falls in Quadrant II (Maintenance Area); and Element 18 (Community publicity facilities: Importance = 3.925 < 4.114, Satisfaction = 3.372 < 3.531) falls in Quadrant III (Low Priority Area).

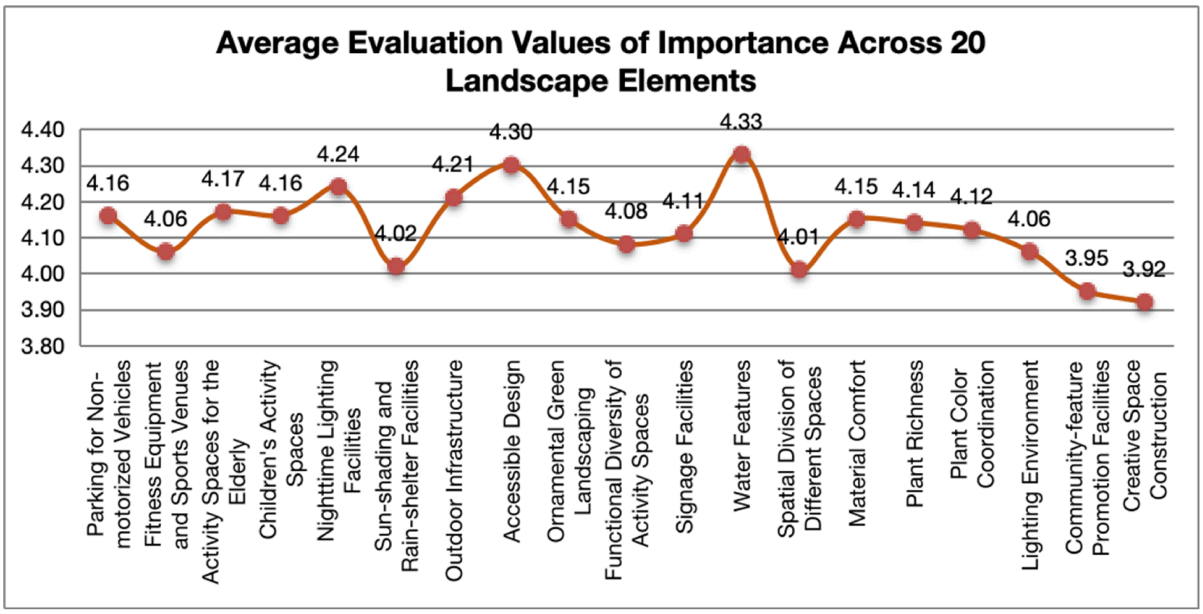


Figure 4. Average Evaluation Values of Importance Across 20 Landscape Elements.

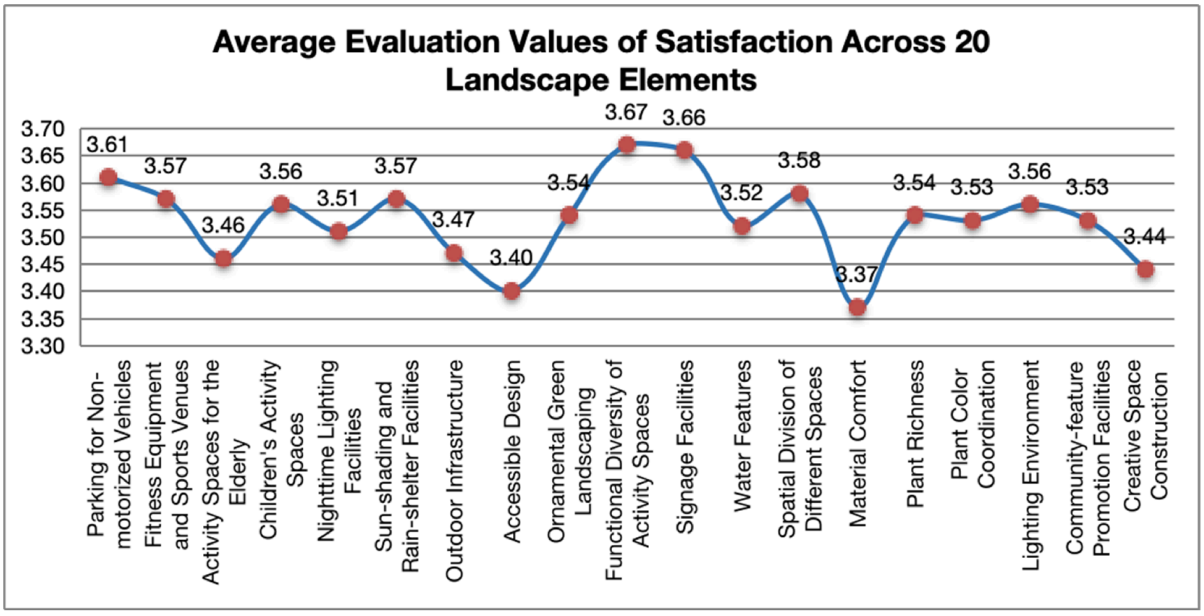


Figure 5. Average Evaluation Values of Satisfaction Across 20 Landscape Elements.

To verify the robustness of quadrant assignments against sampling noise, a comprehensive non-parametric Bootstrap analysis (1000 iterations, resampling respondents with replacement) was conducted across all 20 elements (Figure 6 and Table 4) [21]. Re-sampling confirmed high membership stability for core Quadrant IV repair elements: Element 8 (Barrier-free design, 94.8% probability), Element 14 (Material comfort, 93.2%), and Element 7 (Outdoor infrastructure, 91.6%). Borderline Quadrant IV elements exhibited expected probabilistic distribution: Element 12 (Children's activity venues: 56.5% Quadrant IV/39.8% Quadrant I), Element 5 (Night lighting: 62.4% Quadrant IV/33.1% Quadrant I), and Element 3 (Elderly activity venues: 68.2% Quadrant IV/28.5% Quadrant I). These empirical probabilities confirm that core repair priorities remain structurally stable, while borderline elements (5, 12) are classified as 'sensitive repair elements' whose priority is flexibly adjusted via the integrated Kano–IPA gap ratio.

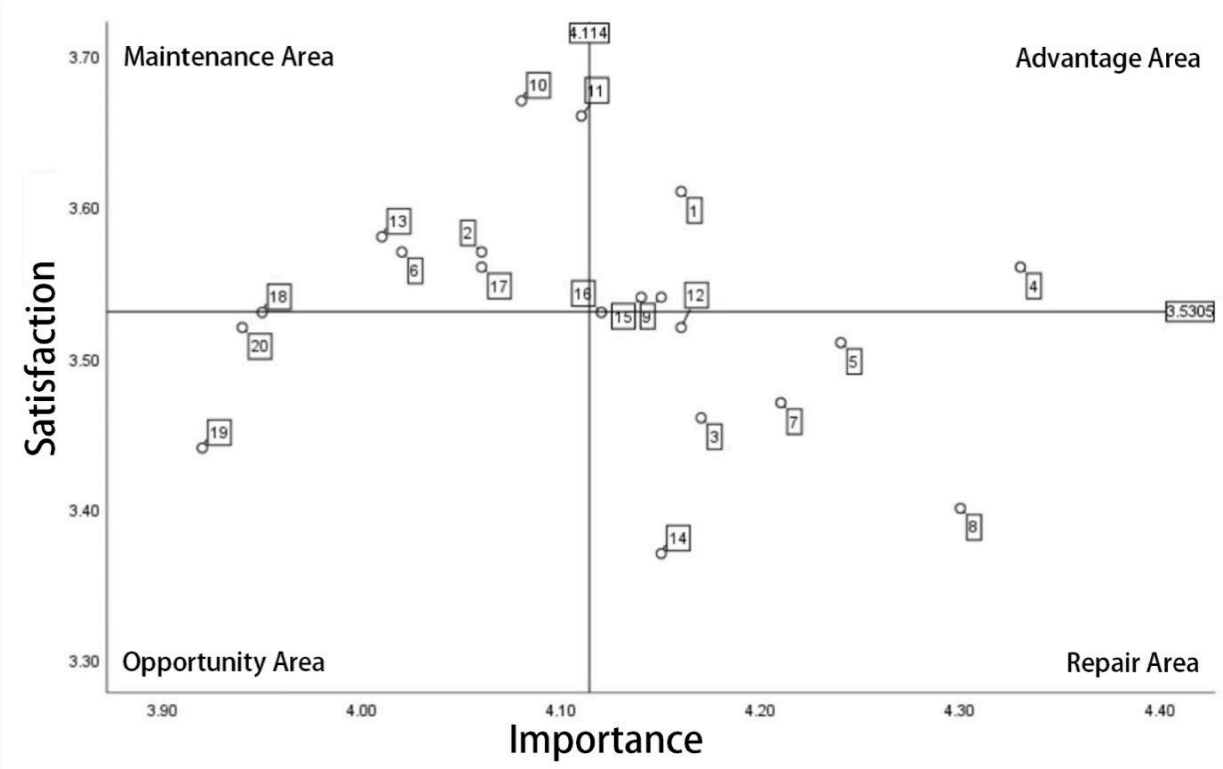


Figure 6. IPA Analysis Matrix Distribution of Landscape Evaluation Elements in Community Public Spaces.

Table 4. IPA Quadrant Classifications and Strategic Improvement Directions.

IPA Quadrant	Perceived Characteristics	Included Elements	Strategic Improvement Direction
Quadrant I	High Importance, High Satisfaction	1, 4, 9, 15, 16	Maintain current standards and optimize details
Quadrant II	Low Importance, High Satisfaction	2, 6, 10, 11, 13, 17	Maintain efficiency without over-allocating resources
Quadrant III	Low Importance, Low Satisfaction	18, 19, 20	Low priority; secondary background transformation
Quadrant IV	High Importance, Low Satisfaction	3, 5, 7, 8, 12, 14	Urgent Repair Area; primary focus for immediate renewal

3.2.3. Integrated Kano–IPA Renewal Priority Ranking

Integrating Kano two-dimensional attributes with IPA quadrants establishes a refined transformation hierarchy (M > O > A > I) [9]. For elements sharing identical Kano classifications within the same IPA quadrant, priority is assigned based on the Importance–Performance Gap Ratio (R = I_mean/S_mean) [10]. The resulting priority sequence is structured as follows:

- Urgent Improvement Sequence (Highest Priority): Barrier-free design (8) > Material comfort (14) > Outdoor infrastructure (7) > Night lighting facilities (5) > Elderly activity venues (3) > Children's activity venues (12).
- Maintenance Sequence: Non-motor vehicle parking (1) > Ornamental green landscape (9) > Sunshade/rainproof facilities (6) > Activity space versatility (10) > Water body design (4) > Plant richness (15) > Fitness venues (2).

3.3. Eye-Tracking Visual Cognitive Data Analysis

3.3.1. Heatmap Distribution and Gestalt Perception

Heatmaps generated from Tobii Pro Lab convert continuous fixation locations into visual density maps (Figure 7) [5,20]. Applying Gestalt psychology (figure-ground segregation and visual continuity):

- Plant Color Schemes: High-saturation, warm-colored flower combinations (red/yellow) generated concentrated red fixation focal points, whereas monochromatic green landscapes produced dispersed visual gaze patterns [22].
- Water Bodies: Centrally structured, regular water bodies established strong visual contrast and geometric order, concentrating gaze duration along water edges [14].
- Space Types: Active social nodes (chess tables, table tennis courts) attracted immediate visual focus, whereas open paved plazas exhibited diffuse fixation trajectories [5,16].



(**a**) Plant Color

(**b**) Water Body Types

(**c**) Space Types

(**d**) Lamp Comparison

(**e**) Sunshade Umbrella Comparison

Figure 7. Eye-tracking Heatmaps of Landscape Elements in Area-Like Spaces: (**a**) Plant Color; (**b**) Water Body Types; (**c**) Space Types; (**d**) Lamp Comparison; (**e**) Sunshade Umbrella Comparison.

The eye-tracking heatmaps in figures share an identical color scale. The color gradient transitions from red through yellow to green, where red indicates higher visual attention.

3.3.2. Quantitative Metric Analysis and One-Way ANOVA

Five eye-tracking metrics—Average Pupil Diameter (mm), Fixation Count, Average Fixation Duration (ms), Blink Count, and Saccade Amplitude (°)—were analyzed across stimulus groups using One-Way ANOVA (N = 30 valid participants, aggregated mean per scene) [5,13].

- Plant Color Richness: Medium color richness elicited significantly higher pupil diameter (3.42 ± 0.18 mm) and fixation duration (385.2 ± 22.4 ms) than high or low richness ($F(2, 27) = 8.64$, $p = 0.001$, $\eta^2 = 0.39$), indicating optimal visual engagement without cognitive overload.
- Water Body Types: Regular water bodies recorded significantly greater pupil dilation (3.38 ± 0.15 mm) compared to natural meandering types ($F(2, 27) = 6.12$, $p = 0.006$, $\eta^2 = 0.31$).
- Space Types: Children's activity spaces and table tennis venues recorded the highest fixation counts ($F(3, 26) = 11.45$, $p < 0.001$, $\eta^2 = 0.57$).

3.3.3. Multi-Method Convergence Analysis

To reconcile observed divergence between implicit visual metrics and explicit subjective ratings (e.g., for children's spaces and sunshade structures), a multi-method convergence matrix was constructed (Figure 8 and Table 5).

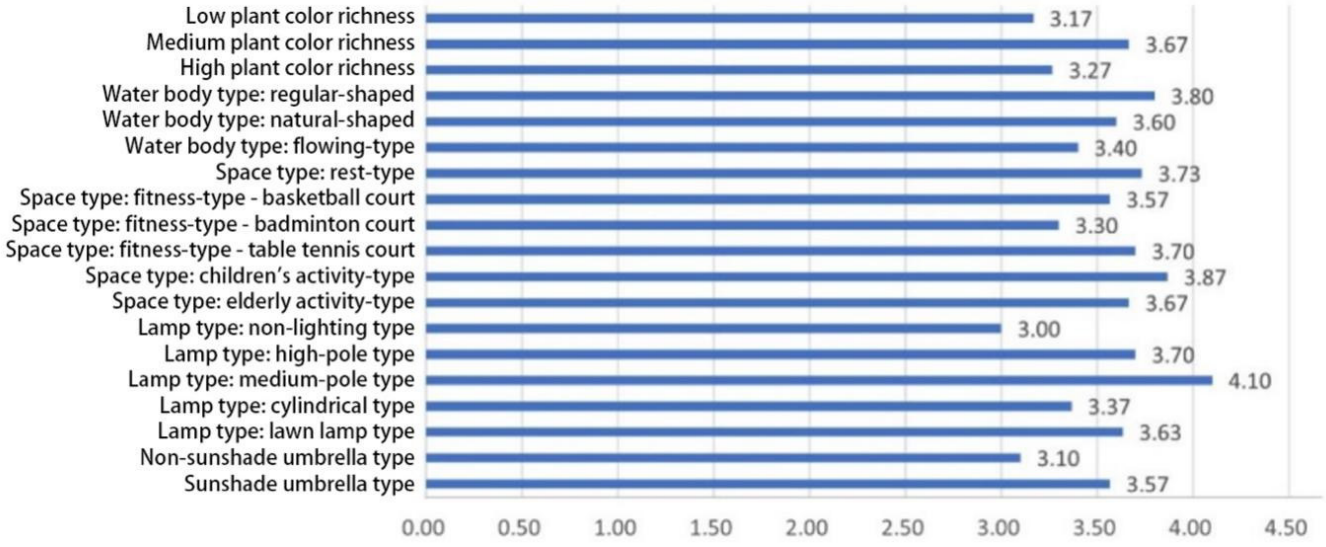


Figure 8. Average Value of Subjective Data in Area-Like Spaces.

As demonstrated in Table 5, divergent metrics do not signify methodological invalidity; rather, they reveal distinct dimensions of human appraisal. High fixation counts indicate complex visual processing and informational search, whereas pupil dilation reflects physiological arousal (modulated by scene luminance), and subjective Likert scores capture conscious functional utility.

Table 5. Multi-Method Convergence Matrix Across Landscape Stimulus Categories (N = 30 aggregated scenes).

Stimulus Category	Heatmap Intensity	Quantitative Eye Metric Direction	Subjective Satisfaction Rating	Convergence Status	Analytical Interpretation of Divergence/Alignment
Plant Color Richness	Concentrated on medium richness	Higher pupil diameter & fixation duration on medium richness	Highest score for medium richness (4.12 ± 0.35)	Fully Convergent	Both physiological arousal and subjective preference favor balanced visual contrast.
Water Body Types	Focused on geometric edges	Larger pupil dilation for regular water body	Highest score for regular water body (3.95 ± 0.41)	Fully Convergent	Clear spatial boundary enhances visual clarity and perceived aesthetic order.
Space Types (Children's Area)	Diffused, moderate focal density	Significantly higher Fixation Count & Duration	Highest satisfaction score (3.87 ± 0.44)	Complementary/Divergent	High Fixation Count reflects visual search friction due to complex spatial elements, whereas high subjective score reflects high functional demand.
Sunshade Structures	High focal concentration on shade canvas	Larger pupil diameter in No-Sunshade condition	Higher score for With-Sunshade (3.57 vs. 3.10)	Complementary/Divergent	Under direct glare/unshaded condition, pupils naturally constrict in response to bright light; transient pupil dilation in No-Sunshade scenes reflects heightened physiological glare stress/arousal, whereas subjective scores prioritize functional shade comfort.

3.4. Multiple Linear Regression Analysis Between Eye-Tracking Metrics and Subjective Satisfaction

To establish a quantitative bridge between physiological visual feedback and subjective satisfaction, a multiple linear regression model was developed [5,16]. The dependent variable was the mean Subjective Satisfaction Score (S), while independent variables comprised the aggregated eye-tracking metrics (N = 30 stimulus scenes) [5,20].

A stepwise regression procedure eliminated three statistically non-significant predictors: Blink Count, Average Fixation Duration, and Saccade Amplitude ($p > 0.10$) [17]. Two core predictors—Average Pupil Diameter (X1, in mm) and Fixation Count (X2, in counts)—were retained in the final model equation:

$$S = 3.825 + 0.485\,X1 - 0.116\,X2 \quad (1)$$

The overall model demonstrated strong explanatory power and statistical significance ($R^2 = 0.618$, Adjusted $R^2 = 0.590$, $F(2, 27) = 21.84$, $p < 0.001$, SE = 0.182) [17]. Multicollinearity diagnostics yielded Variance Inflation Factors (VIF = 1.12 for both X1 and X2, see Table 6), calculated from the inter-correlation between independent variables X1 and X2 ($r = 0.327 \Rightarrow r^2 = 0.107 \Rightarrow VIF = 1/(1 - 0.107) = 1.12$), confirming that collinearity was well below the conservative threshold of 5.0.

Table 6. Stepwise Multiple Linear Regression Parameters for Predicting Subjective Satisfaction (S).

Model Predictors	Unstandardized B	Std. Error (SE)	Standardized β	t-Statistic	*p*-Value	Collinearity (VIF)
(Constant)	3.825	0.412	—	9.28	<0.001	—
Average Pupil Diameter (X1)	0.485	0.115	0.542	4.21	<0.001	1.12
Fixation Count (X2)	−0.116	0.039	−0.381	−2.95	0.006	1.12

Note: Model summary: R = 0.786, R2 = 0.618, Adjusted R2 = 0.590, $F(2, 27) = 21.84$, $p < 0.001$. Variance Inflation Factor (VIF = 1.12) is calculated from the inter-correlation between independent variables X1 and X2 ($r = 0.327$, $r^2 = 0.107 \Rightarrow VIF = 1/(1 - 0.107) = 1.12$), confirming predictor independence.

Interpretation of Regression Coefficients:

1. Average Pupil Diameter (X1): Demonstrates a highly significant positive relationship with subjective satisfaction ($B = 0.485$, $\beta = 0.542$, $p < 0.001$). Dilated pupil diameter serves as a reliable physiological marker of visual interest, positive emotional arousal, and cognitive engagement, indicating that visually stimulating landscape elements directly boost resident satisfaction [13,22].
2. Fixation Count (X2): Exhibits a significant negative relationship with subjective satisfaction ($B = -0.116$, $\beta = -0.381$, $p = 0.006$). An excessively high fixation count reflects elevated visual clutter, informational complexity, or cognitive search friction, where subjects struggle to extract clear spatial organization, thereby dampening overall satisfaction ratings.

4. Results and Discussion

4.1. Synthesis and Cross-Validation of Kano–IPA and Eye-Tracking Findings

This research breaks through the reliance on single-method appraisals in urban micro-renewal by establishing a cross-validated 'physiological–psychological' joint evaluation framework [8,10]. By coupling the Kano–IPA two-dimensional model with quantitative eye-tracking technology, this study elucidates how explicit resident preferences align with—or diverge from—implicit visual cognitive processing [5,13].

Traditional landscape evaluation methods relying solely on one-dimensional Likert questionnaires frequently fail to capture subtle cognitive biases or prioritize competing

transformation demands [1]. In this study, the integrated Kano–IPA model successfully delineated 20 landscape elements into hierarchical quality attributes and strategic quadrants [9]. Notably, Quadrant IV (Concentrate Here/Repair Area) isolated critical baseline deficiencies—such as Barrier-free design (8), Outdoor infrastructure (7), Night lighting (5), and Material comfort (14) [4,6]. These findings align closely with recent empirical studies by Korkmaz and Balaban (2020) and Yıldız et al. (2020), which emphasized that old urban communities in northern China suffer primarily from functional decay and safety infrastructure gaps rather than a shortage of purely aesthetic ornamentation [3,6].

Furthermore, the incorporation of objective eye-tracking metrics provided physiological validation for subjective ratings while uncovering nuances that self-reports overlook [13,16]. As established in the multiple linear regression model (Section 3.4, Equation (1)), Average Pupil Diameter (X1) exhibited a significant positive effect on subjective satisfaction ($\beta = 0.542$, $p < 0.001$), whereas Fixation Count (X2) demonstrated a negative relationship ($\beta = -0.381$, $p = 0.006$). This dual-mechanism confirms that positive emotional arousal (pupil dilation) directly enhances spatial satisfaction, whereas elevated visual search friction (excessive fixation counts) depresses perceived space quality [13].

Reconciling the apparent divergence between implicit metrics and explicit scores (Table 5) represents a key theoretical output of this study [5,14]. For instance, in children's activity spaces, subjects recorded significantly higher Fixation Counts alongside the highest subjective satisfaction ratings (3.87) [5,6]. Rather than indicating methodological contradiction, as cautioned in general eye-tracking literature, this divergence illustrates complementary perceptual dimensions: high fixation counts reflect intense visual information processing driven by spatial element complexity, whereas high subjective scores reflect residents' strong functional aspiration for all-age community facilities [5,16]. Similarly, for sunshade umbrella stimuli, under direct unshaded solar exposure, pupils naturally constrict to bright light; transient pupil dilation in No-Sunshade scenes reflects heightened physiological glare stress, visual discomfort, and emotional arousal, whereas subjective preference ratings prioritized the functional thermal comfort provided by shade structures.

4.2. Theoretical Implications: Extending ART and Visual Cognition in Micro-Renewal

From a theoretical perspective, this study expands the application of Attention Restoration Theory (ART) to the high-density micro-renewal context of northern Chinese urban neighborhoods [7,8]. Kaplan's ART posits that restorative environments require four key components: Being Away, Extent, Fascination, and Compatibility [7,8]. Our findings demonstrate how specific landscape physical attributes trigger these restorative properties:

1. Visual Fascination and Color Psychology: Eye-tracking heatmaps and ANOVA results revealed that plant schemes with medium color richness elicited optimal pupil dilation (3.42 mm) and fixation duration (385.2 ms), outperforming both monochromatic green and excessively variegated plantings [5,22]. This supports the cognitive findings of Mehta and Zhu (2009) and Franěk et al. (2019), confirming that moderate chromatic contrast stimulates involuntary visual attention (Soft Fascination) without causing cognitive fatigue or sensory overload [16,22].
2. Geometric Order and Coherence: Regular, centrally structured water bodies achieved higher gaze concentration and visual satisfaction compared to natural meandering forms [14,15]. In high-density old residential areas characterized by spatial clutter, clean geometric boundaries provide visual order and continuity—core principles of Gestalt psychology—thereby reducing visual search friction and enhancing perceived spatial coherence (Extent) [23].
3. Compatibility and Functional Restorativeness: The high priority assigned to barrier-free facilities, comfortable seating materials, and well-lit walkways underscores that

Spatial Compatibility (the alignment between environmental setting and user intent) is a prerequisite for psychological restoration among aging urban populations [4,24].

4.3. Practical Implications for Urban Planning and Landscape Design

The empirical results translate directly into actionable strategies for urban planners, municipal decision-makers, and landscape architects [1]. We formulate a replicable transformation framework structured around three core dimensions: Functional Repair, Spatial Reconstruction, and Sensory Optimization [1].

4.3.1. Functional Repair: Priority Infrastructure and Barrier-Free Upgrades

In accordance with the Kano–IPA urgent improvement sequence (Section 3.2.3), municipal budget allocation should prioritize baseline infrastructure repairs (Quadrant IV) before embarking on purely aesthetic upgrades:

- All-Age Barrier-Free Systems: Retrofit community pathways with continuous, anti-slip paving, gentle ramps (slope < 1:12) replacing steep steps, continuous handrails, and tactile paving connecting main community entrances to activity nodes.
- Material Comfort and Illumination: Replace cold, damaged stone seating with ergonomically contoured wooden or composite seats featuring thermal comfort. Upgrade night lighting by replacing outdated high-pole glare fixtures with anti-glare, medium-pole LED fixtures (height 2.5–3.5 m) and warm-toned lawn lights (3000 K color temperature) along key circulation paths to improve evening safety perception.

4.3.2. Spatial Reconstruction: Activating Fragmented Nodes and All-Age Zoning

Micro-Space Activation: Apply 'urban acupuncture' techniques to transform underutilized corner lands and informal parking clutter into pocket parks, chess corners, and community gardens [1].

Functional Spatial Zoning: Resolve functional interference between noisy sports activities and quiet rest areas. Buffer dynamic activity zones (e.g., table tennis courts and children's play areas) from residential building facades using multi-layered vegetation belts (trees-shrubs-grass filtering), creating clear spatial hierarchy and acoustic comfort [6,24].

4.3.3. Sensory Optimization: Refined Planting, Water Features, and Pavement

Planting Design: Adopt a 'medium color richness' planting strategy. Utilize non-toxic, native deciduous shade trees (e.g., Ginkgo biloba, Zelkova serrata) combined with seasonal flowering perennial borders (warm red/yellow accents covering 20–30% of green area) to maximize visual engagement without inducing visual clutter [22,24].

Water Body Renovation: Design compact, easy-to-maintain regular or semi-regular water features featuring micro-recirculation, stone edge seating, and shallow water depths (<0.3 m) to ensure safety while fostering water-touching interaction [14,24].

Pavement Guidance: Replace cracked concrete with permeable, shock-absorbing elastic rubber paving in children's and elderly activity zones, using subtle geometric pattern transitions to visually define functional boundaries [24].

4.4. Research Limitations and Future Directions

Despite the scientific rigor achieved through integrated objective–subjective modeling, several limitations should be acknowledged to contextualize the findings:

1. Geographical and Demographic Boundary: The empirical dataset was gathered from Fengcheng Sub-district in Jinan City, representing old residential areas in northern China. Regional climatic differences, cultural customs, and spatial layouts may limit

the direct transferability of specific element rankings to southern humid regions or mega-city contexts.

2. Laboratory Visual Stimuli Constraints: Eye-tracking experiments relied on high-definition 2D digitally rendered static images presented in a controlled laboratory setting. While 2D renderings effectively isolate target landscape variables, they cannot fully replicate full-sensory 3D spatial immersion (including dynamic ambient sound, changing natural daylight, wind velocity, and microclimatic thermal sensations).
3. Pupil Diameter Environmental Sensitivity: Although scene illumination and background contrast were strictly standardized across rendering schemes, pupil diameter remains inherently sensitive to global image luminance and transient cognitive load. Future studies should employ baseline-corrected pupil metrics or eye-tracking integrated with Electroencephalogram (EEG)/Galvanic Skin Response (GSR) to further isolate pure emotional valence from luminance-induced pupillary reflex.
4. Future Research Trajectories: Subsequent research should extend this methodology by: (1) integrating Virtual Reality (VR) headsets and Augmented Reality (AR) spatial simulation to capture real-time physiological responses within dynamic 3D virtual environments; (2) expanding longitudinal post-occupancy evaluations (POE) to track long-term health restoration outcomes after landscape renewal; and (3) embedding Artificial Intelligence (AI) and participatory design platforms to enable real-time resident feedback during community planning stages.

5. Conclusions

This study addresses the long-standing challenge of scientifically identifying residents' authentic landscape preferences in urban micro-renewal by establishing an objective–subjective integrated evaluation framework in Fengcheng Sub-district, Jinan City. By coupling the two-dimensional Kano model and Importance–Performance Analysis (IPA) with quantitative eye-tracking technology, this research breaks through the subjective cognitive biases and recall limitations inherent in traditional single-method appraisals. The primary empirical and theoretical conclusions are summarized as follows:

1. Hierarchical Demand Identification and Strategic Prioritization: Among the 20 evaluated landscape elements, Non-motor vehicle parking (1) was established as a baseline Must-be attribute (M). Quadrant IV (Concentrate Here/Repair Area) isolated six primary deficit elements requiring immediate intervention: Barrier-free design (8), Material comfort (14), Outdoor infrastructure (7), Night lighting facilities (5), Elderly activity venues (3), and Children's activity venues (12). Integrating Kano quality classifications with the Importance–Performance Gap Ratio provided a robust, mathematically grounded renewal priority sequence (M > O > A > I).
2. Physiological–Psychological Coupling and Quantitative Validation: Through rigorous sampling (n = 122 survey respondents; N = 30 valid eye-tracking participants) and data aggregation across stimulus scenes, a stepwise multiple linear regression model was validated ($S = 3.825 + 0.485\ X1 - 0.116\ X2$, $R^2 = 0.618$, $p < 0.001$). The model proves that Average Pupil Diameter (X1) serves as a statistically significant positive predictor of subjective satisfaction ($\beta = 0.542$, $p < 0.001$), reflecting emotional arousal and visual engagement, whereas Fixation Count (X2) exerts a significant negative effect ($\beta = -0.381$, $p = 0.006$), indicating visual search friction caused by spatial clutter. Furthermore, the constructed multi-method convergence matrix successfully reconciled apparent divergences between implicit visual metrics and explicit scores, demonstrating that divergent output channels reveal complementary diagnostic dimensions rather than methodological inconsistency.

3. Theoretical Enrichment and Actionable Design Framework: Theoretically, this study expands Attention Restoration Theory (ART) by demonstrating how specific spatial physical attributes—such as medium plant color richness and regular water feature geometries—foster soft fascination and spatial coherence in high-density northern urban neighborhoods. Practically, the empirical findings are operationalized into a structured 'demand priority–space type–design method' transformation framework spanning three core dimensions: Functional Repair (upgrading barrier-free systems and seating/lighting ergonomics), Spatial Reconstruction (activating pocket nodes and enforcing all-age zoning), and Sensory Optimization (calibrating plant color contrast, pavement elasticity, and water edge interaction).

In conclusion, this objective–subjective joint evaluation methodology provides a transparent, replicable, and data-driven decision-making path for urban planners, landscape architects, and municipal authorities. To overcome current laboratory image constraints, future research will extend this framework by integrating dynamic 3D Virtual Reality (VR) immersion, multi-channel physiological monitoring (e.g., EEG and Galvanic Skin Response), and Artificial Intelligence (AI)-driven community participatory planning platforms, further driving the human-centric, sustainable renewal of urban residential environments.

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