

Article

Resident Heterogeneity in Health-Promoting Street Renewal: Evidence from Health Literacy—Activity Behavior Mismatch in Old Urban Neighborhoods

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Abstract

Responding to residents' differentiated health-promoting needs has become important for improving the adaptability of street renewal in old urban neighborhoods. Based on 1404 valid questionnaires from residents in old urban neighborhoods of Jinan, China, this study develops an analytical framework linking group classification, environmental responses, and renewal strategies from the perspective of health literacy–activity behavior mismatch. Health literacy and activity behavior indices were constructed, and K-means clustering was used to identify mismatch groups. Estimated marginal means, average marginal effects, and multiple-response analysis were then employed to compare group-specific response trajectories and improvement preferences across four street environmental dimensions: slow-mobility space, service function, natural aesthetics, and activity facilities. Further interpretation of the obtained analytical results demonstrates that the investigated resident samples are partitioned into four typical subgroups: behavior-driven, high-literacy/high-behavior, literacy-driven, and low-literacy/low-behavior groups. Slow-mobility space was mainly associated with participation willingness and mismatch adjustment; natural aesthetics was primarily related to environmental cognition and perceived attractiveness; activity facilities were more relevant to mismatch changes among low-literacy/low-behavior residents; and service function mainly provided everyday convenience support. Improvement preferences were generally concentrated on basic environmental conditions, especially traffic safety, natural environment, and public activity spaces. These findings provide empirical evidence for group-based health-promoting street renewal and highlight its relevance to socially inclusive and sustainable urban regeneration.

Keywords: sustainable urban renewal; old urban neighborhoods; health-promoting street renewal; street environment; health literacy–activity behavior mismatch; resident heterogeneity



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1. Introduction

1.1. Research Background

With the continued development of healthy city initiatives, health-related concerns have gradually shifted from disease intervention and risk control to health promotion. Health promotion emphasizes healthier lifestyles and supportive environments that enable individuals to form and maintain healthy behaviors [1]. Against the background of increasing chronic disease burdens, insufficient physical activity, and population aging, whether the built environment can provide sustained support for residents' everyday

health-promoting activities has become a shared concern in urban planning and public health research [2].

Old urban neighborhoods are among the most direct and frequently used settings for residents' everyday activities. For older adults, children, and people with limited mobility, neighborhood streets not only serve as movement corridors but also support walking, exercise, staying, social interaction, and leisure activities. Therefore, the safety, comfort, convenience, and attractiveness of street spaces can shape the opportunities and continuity of residents' activity behavior [3]. However, many old urban neighborhoods in China still face aging street facilities, insufficient functional provision, and a shortage of public activity spaces. These problems, including discontinuous slow-mobility systems, pedestrian–vehicle conflicts, inadequate activity facilities, and limited neighborhood service support, may reduce opportunities for walking, physical activity, and social interaction [4].

In China, old urban neighborhood renewal is gradually expanding from infrastructure repair to public space improvement, service enhancement, and community revitalization. In this transition, street environments are not only objects of physical upgrading but also spatial carriers for supporting health-promoting behavior and responding to differentiated health needs. Because residents differ in health cognition, behavioral motivation, participation willingness, and actual activity behavior, identifying resident heterogeneity and revealing group-specific street environmental responses and improvement needs are important for improving the adaptability and targeting of renewal interventions.

1.2. Research Progress

Previous studies have shown close associations between street environments and residents' health. High-quality built environments can support physical activity, mental restoration, and social connections by improving walking accessibility, spatial attractiveness, restorative experiences, and opportunities for social interaction [5,6]. Recent research has gradually shifted from examining whether street environments are associated with health outcomes to exploring how they shape health promotion through individual cognition, perception, and behavioral mechanisms.

Health literacy is an important concept for understanding this process. Conventionally, it refers to individuals' ability to access, understand, evaluate, and use health information to make health-related decisions. In the context of street-based health promotion, this study [7] operationalizes health literacy as residents' behavioral motivation, cognitive ability, and willingness to participate in health-promoting activities supported by neighborhood street environments. Correspondingly, activity behavior refers to residents' actual and observable behaviors in public street environments, such as walking, running, social interaction, sitting, and leisure activities.

Health literacy and activity behavior are two key dimensions of residents' health-promoting status. Existing studies generally suggest that higher health literacy is associated with more active lifestyle choices, better health management capacity, and more favorable health behavior performance [8–10]. However, health literacy does not always translate into action. Conner and Norman [11] noted that the intention–behavior gap is particularly evident in physical activity. Thus, some residents may have relatively high health cognition and participation willingness but find it difficult to maintain stable activity behavior, whereas others may frequently engage in activities while having limited health cognition or limited understanding of environmental support. This gap suggests that evaluating the health-supportive role of street environments from either health literacy or activity behavior alone is insufficient for explaining differentiated resident responses. Compared with studies that examine health literacy, behavioral intention, or physical activity separately, a health literacy–activity behavior mismatch perspective focuses on the relative

relationship between residents' internal health-promoting capacity and their actual street-based activity behavior. This perspective helps reveal whether residents' health cognition, motivation, and willingness are aligned with their actual activity behavior, and whether discrepancies exist in different directions or to different degrees. By shifting the focus from a single health-promoting attribute to the relationship between internal capacity and external behavior, this framework provides a theoretical basis for identifying heterogeneous resident groups and for examining their differentiated responses to street environments and renewal needs. This also provides a basis for more inclusive and resource-efficient renewal decisions, thereby linking health-promoting street renewal with socially sustainable urban regeneration (Figure 1).

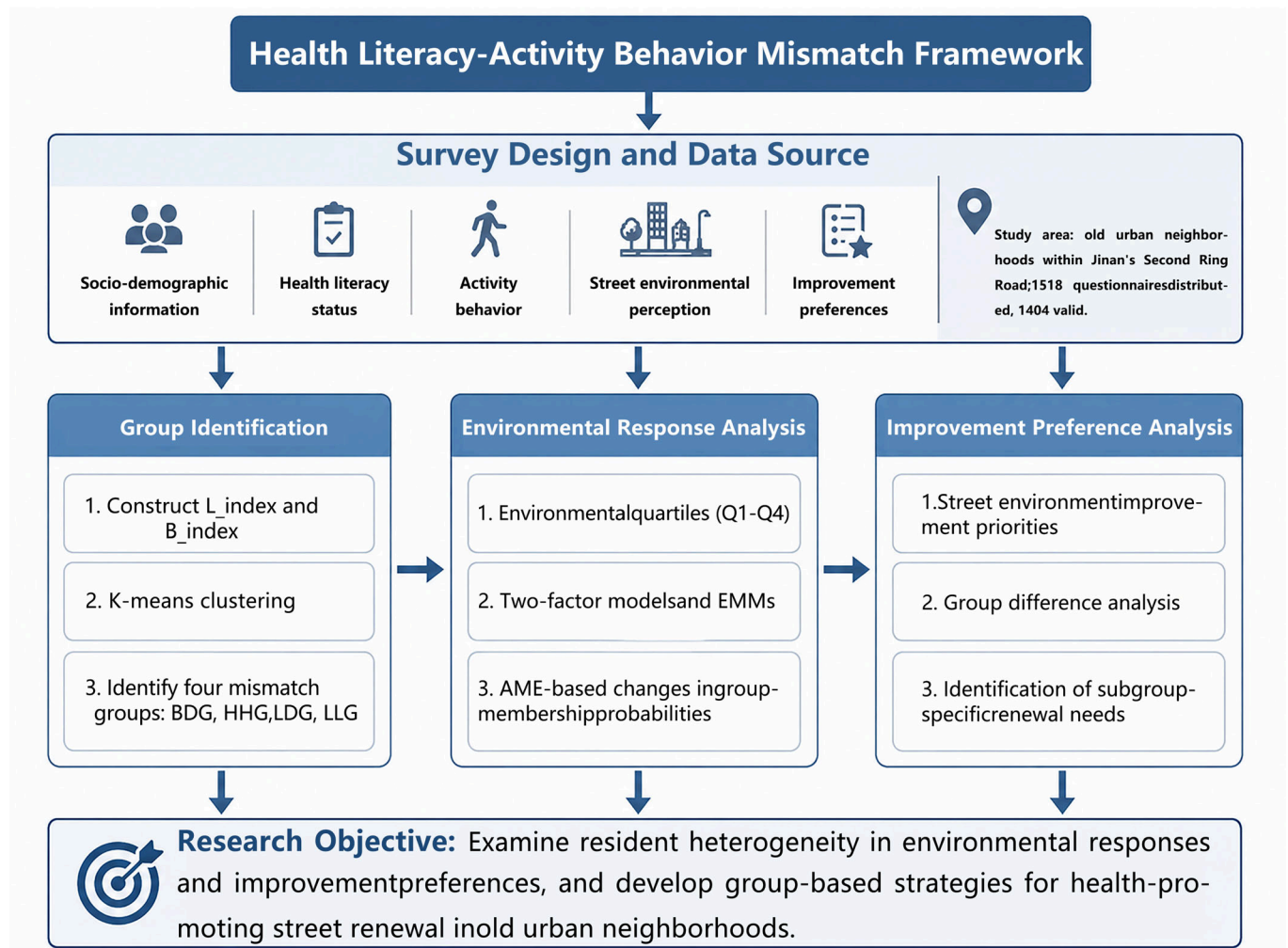


Figure 1. Analytical Framework Based on Health Literacy–Activity Behavior Mismatch among Residents in Old Urban Neighborhoods.

1.3. Research Objectives and Framework

Based on this background, this study uses the mismatch between residents' health literacy and activity behavior in old urban neighborhoods as its analytical starting point and develops a framework linking group classification, environmental responses, and renewal strategies.

It addresses three questions: first, how can residents be classified according to the relationship between their health literacy index and activity behavior index? Second, do different mismatch groups show differentiated responses to street environmental dimensions, including slow-mobility space, service function, natural aesthetics, and activity

facilities? Third, how do improvement preferences differ among groups, and how can these differences inform strategies for health-promoting street renewal?

To answer these questions, this study first constructs a health literacy index and an activity behavior index and identifies health literacy–activity behavior mismatch groups. It then compares the response trajectories of different groups across street environmental gradients. Finally, it summarizes group-specific preferences for street environmental improvements and proposes group-based strategies for health-promoting street renewal.

2. Materials and Methods

2.1. Questionnaire Design and Indicator Selection

Previous studies have shown that the inclusiveness, convenience, aesthetic quality, and functionality of urban street public spaces are closely associated with residents' activity behavior and cognitive experience [12,13]. From the perspective of activity behavior, factors such as traffic safety, landscape perception, facility provision, slow-mobility continuity, service accessibility, and spatial quality may influence residents' route choices, activity frequency, healthy lifestyle choices, and social interaction [14–18].

Compared with the literature linking street environments to activity behavior, direct research on the relationship between street environments and health literacy remains relatively limited. Existing studies have more often explained this relationship through health-supportive environments, restorative perception, and environmental evaluation. For example, greenery, spatial openness, streetscape quality, visual environment, and pedestrian friendliness may influence residents' judgments of restoration, comfort, health supportiveness, and activity attractiveness [19–21]. Therefore, in this study, health literacy was operationalized in the context of street-based health promotion through three dimensions: behavioral motivation, cognitive ability, and participation willingness. These dimensions were used to reflect the internal conditions that support residents' health-promoting activity behavior in street spaces.

Based on this evidence, a questionnaire consisting of five modules was designed (Figure 2). The first module collected socio-demographic information, including age, gender, educational attainment, length of residence, and household structure. The second module measured health literacy through behavioral motivation, cognitive ability, and participation willingness. Behavioral motivation included enjoyment, stress relief, social interaction, disease prevention, health responsibility, and healthy dietary needs. Cognitive ability concerned residents' understanding of the relationship between street environments, health status, health behavior, and the importance of healthy lifestyles. Participation willingness focused on the attractiveness of different street environmental dimensions for activity participation. The third module measured activity behavior, including activity frequency, activity duration, and activity type. The fourth module assessed residents' perceptions of street environmental elements in their neighborhood. The fifth module collected residents' preferences for street environmental improvement. The street environmental perception indicators were developed by integrating and adapting previous studies on walkability, service accessibility, restorative environments, public space quality, and activity-supportive facilities, and were further contextualized to old urban neighborhood renewal in Jinan. Accordingly, an initial pool of 24 street environmental indicators was established.

Before constructing the street environmental evaluation dimensions, the reliability and validity of the initial 24-item scale were examined. The results showed that the overall Cronbach's alpha was 0.946, the standardized alpha was 0.947, the KMO value was 0.964, and Bartlett's test of sphericity was significant at the 0.001 level, indicating that the scale had high internal consistency and was suitable for factor analysis. Exploratory factor analysis (EFA) and principal component analysis (PCA) were then used to examine the

dimensional structure and item loadings. The results showed that the EFA pattern loading and PCA rotated loading of the sound environment item were substantially lower than those of the other street environmental indicators; therefore, this item was removed from the subsequent evaluation system. After this refinement, 23 indicators were retained and grouped into four dimensions: slow-mobility space, service function, natural aesthetics, and activity facilities (Table 1).

Structure and Content of the Questionnaire

The questionnaire consists of five modules: socio-demographic information, health literacy, activity behavior, street environmental perception, and improvement preferences.

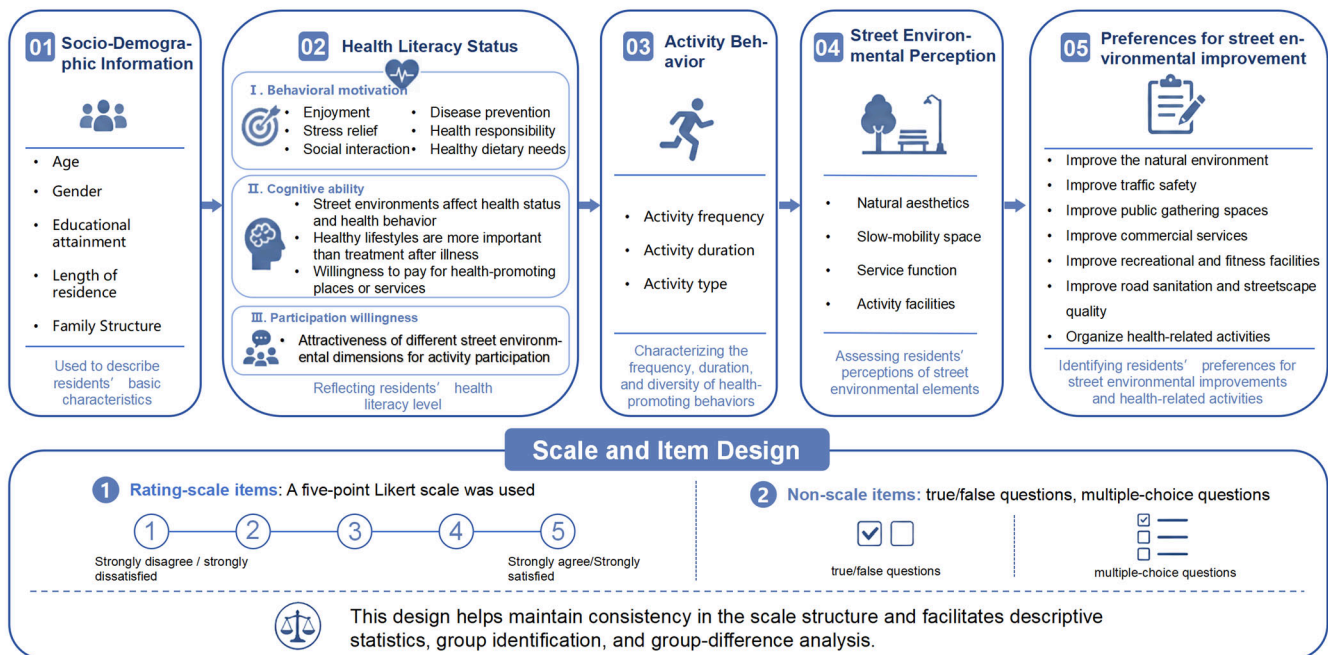


Figure 2. Questionnaire structure and item design.

Table 1. Dimensions, components, and factor loadings of perceived street environmental elements.

Dimension	Code	Environmental Element	Description	EFA Pattern Loading	PCA Rotated Loading
A. Slow-Mobility Space	A1	Safety Facilities	Status of street safety signage, such as traffic lights and traffic signs	0.557	0.632
	A2	Lighting Infrastructure	Street lighting conditions on both sides of the street	0.414	0.538
	A3	Pedestrian–Vehicle Separation	Adequacy of separation measures between pedestrian/bicycle lanes and vehicle lanes	0.535	0.615
	A4	Sidewalk Quality	Sidewalk width and pavement condition	0.918	0.78
	A5	Bicycle Lane Quality	Bicycle lane width and pavement condition	0.695	0.69
	A6	Street Connectivity	Connectivity and accessibility between streets	0.618	0.661
	A7	Spatial Openness	Degree of spatial openness of the street	0.823	0.734
	A8	Vehicle Disturbance	Density of moving and parked vehicles on the street	0.687	0.674
B. Service Function	B1	Number of Service Facilities	Number of service facilities	0.696	0.72
	B2	Types of Service Facilities	Diversity of service facilities	0.76	0.756
	B3	Quality of Service Facilities	Quality of service facilities	0.826	0.789
	B4	Recreational and Cultural Facilities	Availability of cultural and recreational facilities, such as bookstores and exhibition spaces	0.811	0.782
	B5	Daily Living Facilities	Availability of daily-life service facilities, such as supermarkets and markets	0.835	0.794

Table 1. Cont.

Dimension	Code	Environmental Element	Description	EFA Pattern Loading	PCA Rotated Loading
C. Natural Aesthetics	C1	Greening Level	Greenery coverage and visibility of greenery within the field of view	0.658	0.639
	C2	Plant Diversity	Diversity of vegetation colors within the field of view	0.685	0.741
	C3	Pocket Parks	Availability of small parks with recreational functions along the street	0.598	0.634
	C4	Street-Facing Building Facades	Enclosure, continuity, and aesthetic quality of building facades along the street	0.669	0.599
	C5	Street Cleanliness	Street cleanliness and maintenance condition	0.514	0.51
	C6	Cultural Landscapes	Cultural or artistic features along the street, such as posters and sculptures	0.677	0.619
D. Activity Facilities	D1	Fitness Facilities	Availability of fitness facilities	0.79	0.733
	D2	Recreational Facilities	Availability of recreational facilities, such as benches and pavilions	0.839	0.761
	D3	Playground Facilities	Availability of playground equipment, such as slides and sandboxes	0.702	0.731
	D4	Public Activity Areas	Open-air spaces within the neighborhood that are accessible and suitable for leisure and exercise	0.762	0.717

Note: Cronbach's $\alpha = 0.946$, standardized $\alpha = 0.947$, KMO = 0.964, and Bartlett's test of sphericity was significant ($\chi^2 = 19437.615$, $df = 276$, $p < 0.001$). The sound environment item was excluded because both its EFA pattern loading and PCA rotated loading were lower than 0.40 and substantially lower than those of the other items. The remaining 23 items were retained in the final indicator system. EFA = exploratory factor analysis; PCA = principal component analysis.

2.2. Study Area and Sample Source

Jinan is the capital city of Shandong Province, China, and a nationally recognized historic and cultural city. Its old urban areas have a long development history, a relatively high population concentration, and well-preserved street and lane patterns. These areas support typical everyday street functions but also face problems such as limited public activity spaces, aging street facilities, and insufficient health-supportive environmental conditions. According to the Jinan Urban Renewal Special Plan (2021–2035), old urban neighborhoods in Jinan are mainly distributed within the Second Ring Road of the central urban area, with a total building area of approximately 65.81 million m^2 and about 731,000 households. By 2025, the city plans to renovate approximately 21.53 million m^2 of old residential compounds, involving about 267,000 households.

Based on this context, the area within the Second Ring Road of Jinan was selected as the initial study area. Using the number of households in residential compounds built before 2005, the street-level resident population from the Seventh National Population Census, and the average household size, this study constructed an indicator representing the estimated proportion of residents living in old residential compounds. This indicator was used to measure the concentration of old residential spaces across subdistricts. The formula is as follows:

$$R_i = \frac{H_i \times 2.69}{P_i} \quad (1)$$

where R_i denotes the estimated proportion of residents living in pre-2005 residential compounds in subdistrict; H_i denotes the total number of households in residential compounds built before 2005 in subdistrict; P_i denotes the resident population of subdistrict; and 2.69 denotes the average household size. The results showed that approximately 41% of the subdistricts had an R_i value greater than 0.4, forming a relatively clear separation from other areas in the empirical distribution. Therefore, subdistricts with $R_i \geq 0.4$ were selected as the sample areas (Figure 3).

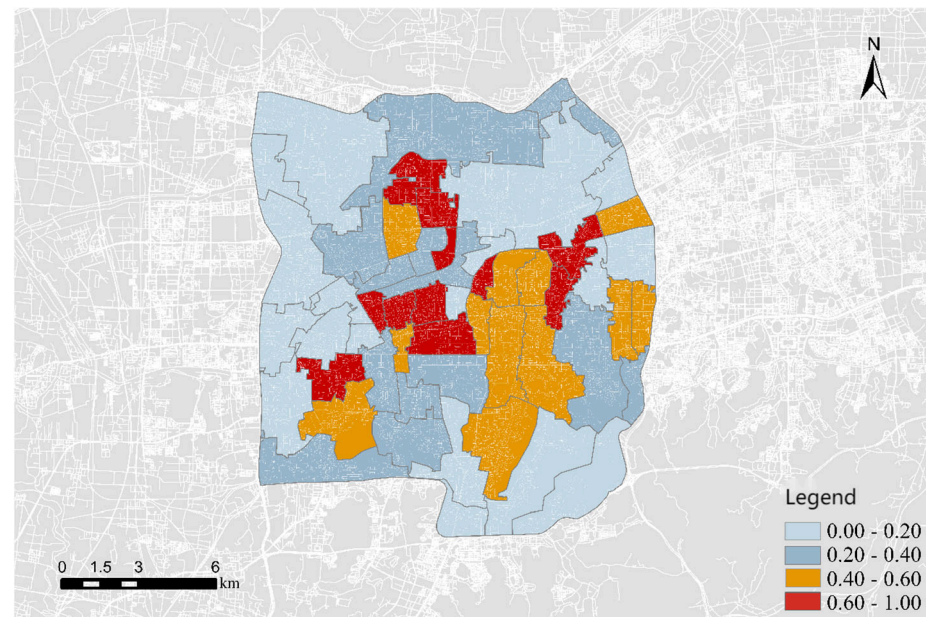


Figure 3. Spatial distribution of the estimated proportion of residents living in old residential compounds within Jinan's Second Ring Road.

The survey was conducted in the selected sample areas from March to November 2025. The questionnaire survey was conducted in public street spaces with the assistance of local neighborhood committees. Before the field survey, the research team contacted local neighborhood committees to assist in recruiting eligible respondents. Respondents were required to have lived in the sampled area for at least six months and to have had outdoor activity experience within the survey area during the previous week. These criteria ensured that respondents were familiar with the local street environment and had recent experience relevant to evaluating its influence on their activity behavior.

To reduce possible temporal bias, daily surveys were conducted in two periods: 7:00–11:00 and 14:00–17:00. During fieldwork, questionnaires were distributed across multiple sites with the assistance of local community staff, and the research team attempted to include residents with different socio-demographic characteristics and street-use patterns. A total of 1518 questionnaires were distributed. After manually excluding questionnaires with missing key variables and obviously invalid responses, 1404 valid questionnaires were retained for analysis.

2.3. Data Processing and Analytical Methods

Based on the valid questionnaire data, the analysis was conducted in four steps: index construction, group identification, environmental response analysis, and improvement preference analysis. K-means clustering, estimated marginal means (EMMs), average marginal effects (AME), and multiple-response analysis (MRA) were used. First, the health literacy index and activity behavior index were constructed. To eliminate dimensional differences among variables, all relevant variables were standardized as follows:

$$Z_{ij} = \frac{X_{ij} - \bar{X}_j}{SD_j} \quad (2)$$

where Z_{ij} denotes the standardized value of respondent i on variable j , X_{ij} denotes the original value, and $\bar{X}_j$ and SD_j denote the mean and standard deviation of variable j , respectively. The two indices were then calculated using the equal-weighted mean method:

$$L_i = \frac{Z_{BM_i} + Z_{CA_i} + Z_{PI_i}}{3} \quad (3)$$

$$B_i = \frac{Z_{BF_i} + Z_{BT_i} + Z_{BD_i}}{3} \quad (4)$$

where L_i denotes the health literacy index of respondent i , and B_i denotes the activity behavior index. BM, CA, and PI represent behavioral motivation, cognitive ability, and participation willingness, respectively, while BF, BT, and BD represent activity frequency, activity duration, and activity diversity, respectively. For consistency and comparability between the two indices, the three standardized components of each index were averaged with equal weights. This approach avoids assigning additional subjective weights and allows health literacy and activity behavior to be compared on the same standardized scale.

Second, health literacy–activity behavior mismatch groups were identified. K-means clustering was applied using standardized L_i and B_i as clustering variables to identify different literacy–behavior relationship types. To further characterize the structural deviation between activity behavior and health literacy, the mismatch index M_i and absolute mismatch index AM_i were defined as follows:

$$M_i = B_i - L_i \quad (5)$$

$$AM_i = |B_i - L_i| \quad (6)$$

where $M_i > 0$ indicates that the activity behavior index is higher than the health literacy index, representing a behavior-leading pattern; $M_i < 0$ indicates that the health literacy index is higher than the activity behavior index, representing a literacy-leading pattern; and AM_i represents the absolute gap between the two indices, with larger values indicating a higher degree of mismatch.

Third, differentiated responses to street environmental dimensions were compared across groups. The four dimensions—slow-mobility space, service function, natural aesthetics, and activity facilities—were divided into quartiles (Q1–Q4) according to the sample distribution. A two-factor framework of “environmental quartile $\times$ group type” was then constructed. Behavioral motivation, cognitive ability, participation willingness, the mismatch index, and the absolute mismatch index were used as outcome variables to test the main effects of environment and group, as well as their interaction effects. The models controlled for socio-demographic variables, including age, gender, educational attainment, length of residence, and household structure.

To present group response trajectories under different environmental levels, EMMs were extracted, and partial η^2 was used to compare the strength of associations between environmental dimensions and group responses. Because group types were identified from the health literacy and activity behavior indices, between-group differences in behavioral motivation, cognitive ability, and participation willingness have a certain constructed nature. Therefore, this analysis did not aim to re-test baseline group differences, but to examine within-group response trajectories and their changes across environmental gradients.

In addition, AME was used to estimate the average change in group membership probability associated with a one-standard-deviation increase in each street environmental dimension. AME was calculated based on a multinomial logit model, with mismatch group type as the dependent variable and the four street environmental dimensions as explanatory variables. Socio-demographic variables were included as controls. This method reflects, at the model-predicted level, the direction and relative strength of associations between street environmental dimensions and group structure.

Fourth, group differences in street environmental improvement preferences were identified. The improvement items included traffic safety, natural environment, commercial services, public activity spaces, road sanitation, recreational and fitness facilities, and health-related activities. Because respondents could select multiple items, MRA was used to capture the combined characteristics of improvement preferences. Chi-square tests and Cramer's V were further used to compare the significance and effect size of group differences across improvement items.

3. Results

3.1. Sample Characteristics, Health Literacy, and Identification of Mismatch Groups

The respondents covered a broad age range, with adults forming the main body of the sample. In terms of socio-demographic characteristics, 63.8% had an educational level below a bachelor's degree, and 88.0% reported a monthly income below CNY 10,000. Nearly half of the respondents had lived in old urban neighborhoods for more than five years, and the dominant household structures were couple-only and two-generation households, indicating a relatively stable residential base and household structure. The detailed socio-demographic characteristics of the respondents are shown in Table 2.

Table 2. Socio-demographic characteristics of respondents ($n = 1404$).

Demographic Attribute	Category	Sample Size (n)	Percentage (%)
Gender	Male	793	56.5
	Female	611	43.5
Age group	<18 years	32	2.3
	18–30 years	281	20
	31–45 years	312	22.2
	46–59 years	385	27.4
	≥ 60 years	394	28.1
Educational attainment	Junior high school or below	268	19.1
	High school/Vocational	313	22.3
	Associate degree	315	22.4
	Bachelor's degree	365	26
	Master's degree or above	143	10.2
Monthly income	$<0.2 \times 10^3$ CNY	256	18.2
	$0.2\text{--}0.5 \times 10^3$ CNY	486	34.6
	$0.5\text{--}1 \times 10^3$ CNY	494	35.2
	$1\text{--}2 \times 10^3$ CNY	132	9.4
	$\geq 2 \times 10^3$ CNY	36	2.6
Length of residence	≤ 1 year	174	12.4
	1–3 years	269	19.2
	3–5 years	291	20.7
	>5 years	670	47.7
Household structure	Single	201	14.3
	Couple-only	451	32.1
	Two-generation	549	39.1
	Three-generation	203	14.5

In terms of activity behavior (Table 3), approximately 95% of the residents reported engaging in activities within the neighborhood more than one day per week, and 27.6% reported going out for activities almost every day. Nearly 70% of the residents spent 0.5–3 h on each activity occasion. The main activity periods were concentrated during 06:00–12:00 and 18:00–21:00. The reported activities were mainly low- to moderate-intensity

leisure activities. Walking, running, and cycling were the most common types, followed by social activities such as chatting and chess or card games. Overall, public streets in old urban neighborhoods remained important everyday settings for residents' daily activities, leisure stays, and neighborhood interactions.

Table 3. Characteristics of residents' activity behavior.

Category	Item	Sample Size (<i>n</i>)	Percentage (%)
Activity frequency (days/week)	1	74	5.3%
	2–3	529	37.7%
	4–5	413	29.4%
	6–7	388	27.6%
Activity duration (h/occasion)	<0.5	288	20.5%
	0.5–1.5	547	39.0%
	1.6–3	417	29.7%
	>3	152	10.8%
Activity time period	06:00–12:00	730	52.0%
	13:00–17:00	344	24.5%
	18:00–21:00	813	57.9%
Activity type	Walking/Running/Cycling	949	67.6%
	Ball games/Tai Chi/Dancing	358	25.5%
	Chatting/Chess and card games	497	35.4%
	Walking with children/Dog walking	371	26.4%
	Sitting/Viewing scenery/Reading	353	25.1%
	Gardening	77	5.5%
	Others	97	6.9%
Activity diversity	One activity	508	36.2%
	Moderate diversity (2–3 activities)	841	59.9%
	High diversity (>3 activities)	55	3.9%

Note: Activity time period and activity type were multiple-choice items; therefore, their percentages may exceed 100%.

To further clarify the age coverage of neighborhood activity behavior, activity frequency, duration, and diversity were compared across age groups (Figure 4). The results show that residents of different age groups all participated in neighborhood street activities, although their activity patterns varied to some extent. The ≥ 60 age group showed relatively higher proportions in high-frequency activity, whereas other age groups were more concentrated in moderate-frequency categories. Across age groups, activity duration was mainly concentrated within 0.5–3 h, and moderate activity diversity was the dominant pattern.

Regarding health literacy, behavioral motivation, cognitive ability, and participation willingness were all significantly and positively correlated (Table 4). Their mean values were 3.757, 3.478, and 3.360, respectively, indicating relatively high behavioral motivation, moderate cognitive ability, and lower participation willingness. At the item level, “reducing illness” received the highest score in the behavioral motivation dimension, followed by “stress relief” and “social interaction,” suggesting that residents' street-based activity motivation was mainly related to disease prevention, stress regulation, and social connection. In the cognitive ability dimension, residents showed relatively high recognition of the importance of healthy lifestyles but lower awareness of how street environments affect health status and health behavior. In the participation willingness dimension, all four street environmental dimensions showed some attractiveness, with natural landscape quality receiving the highest score (Mean = 3.450).

The study then constructed a mismatch analytical framework based on the activity behavior index (*Bi*) and health literacy index (*Li*). *Bi* consisted of activity frequency (BF), activity duration (BT), and activity diversity (BD), while *Li* consisted of behavioral motivation (BM), cognitive ability (CA), and participation willingness (PI). After standardization, the two indices were calculated using the equal-weighted mean method. A two-dimensional feature space was then constructed using *Bi* and *Li*, and K-means clustering was applied to classify the sample.

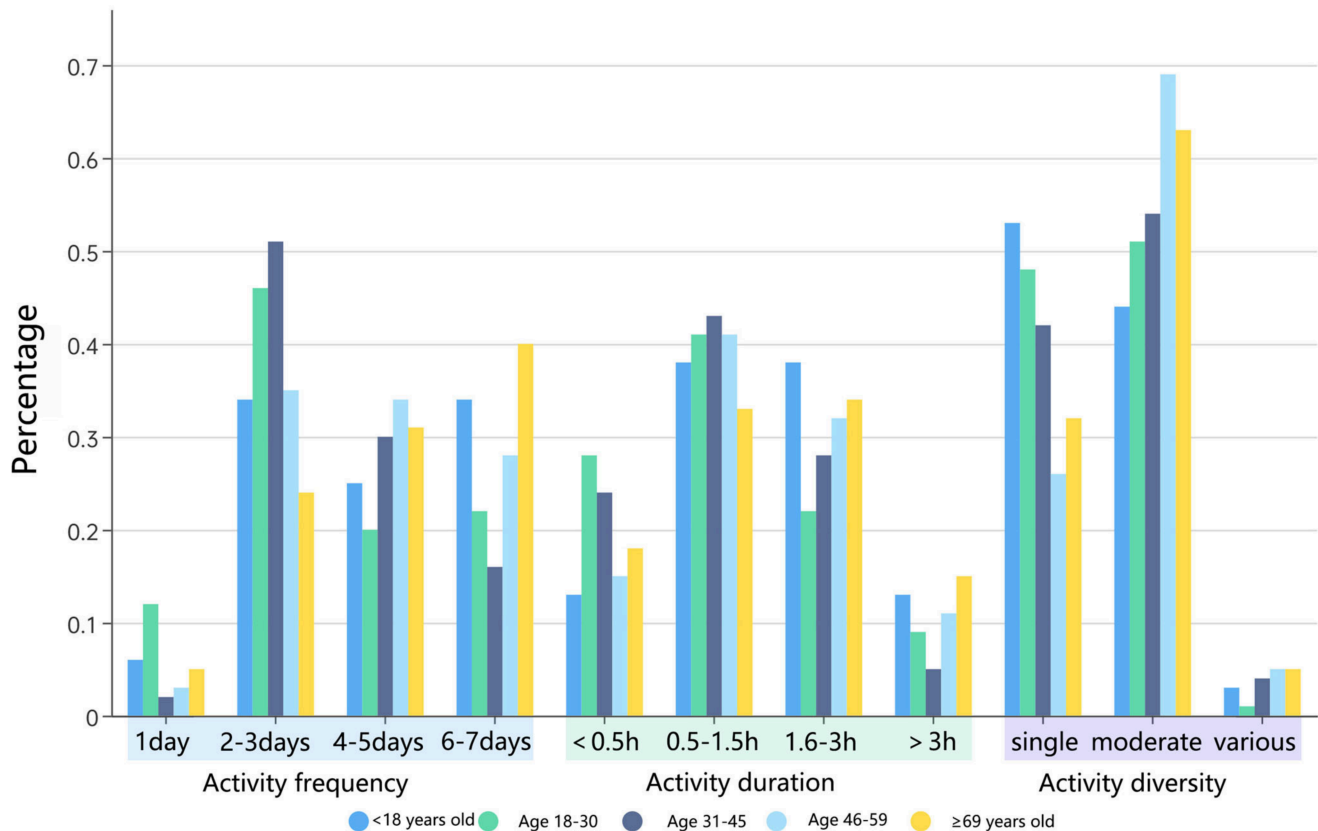


Figure 4. Activity behavior characteristics across age groups.

Table 4. Descriptive statistics and correlation coefficients of residents' health literacy variables ($n = 1404$).

Variable	Mean	SD	Behavioral Motivation	Cognitive Ability	Participation Willingness
Behavioral Motivation	3.757	0.942	1		
Cognitive Ability	3.478	0.805	0.589 **	1	
Participation willingness	3.360	0.948	0.538 **	0.583 **	1

Note: indicates a statistically significant correlation (r), ** $p < 0.01$.

To justify the selection of the number of clusters, clustering solutions from $k = 2$ to $k = 6$ were compared using SSE, Silhouette, Calinski–Harabasz, and Davies–Bouldin indices, together with theoretical interpretability (Table 5). The two-cluster solution was too coarse to distinguish the direction of mismatch, while the five- and six-cluster solutions produced more fragmented classifications without adding clear theoretical types. Although $k = 4$ was not optimal for every single statistical index, it provided the best correspondence with the proposed mismatch framework and achieved a balance between statistical performance, interpretability, and parsimony. Therefore, $k = 4$ was retained for subsequent analysis. The clustering process converged after 13 iterations, and the two clustering variables showed significant between-group differences.

In group interpretation, residents whose activity behavior level was higher than their health literacy level were defined as the behavior-driven group, while those whose health literacy level was higher than their activity behavior level were defined as the literacy-driven group. Meanwhile, residents with both *Bi* and *Li* above the sample mean were defined as the high-literacy/high-behavior group, whereas those with both indices below the sample mean were defined as the low-literacy/low-behavior group. The clustering results (Table 6) identified four mismatch groups: the behavior-driven group (BDG), high-literacy/high-behavior group (HHG), literacy-driven group (LDG), and low-literacy/low-behavior group (LLG). HHG accounted for the largest proportion of the sample, at 31.55%, with both activity behavior and health literacy levels above the sample average. BDG accounted for 29.42%, with activity behavior higher than health literacy, reflecting a behavior-leading pattern. LDG accounted for 26.42%, with health literacy higher than activity behavior, reflecting a literacy-leading pattern. LLG accounted for the smallest proportion, at 12.61%, with both activity behavior and health literacy below the sample average, making it a key group for subsequent health-promoting street renewal.

Table 5. Comparison of clustering solutions ($k = 2-6$).

k	SSE	Silhouette	Calinski-Harabasz	Davies-Bouldin	Interpretation
2	1401.228	0.424	1407.548	0.892	Too coarse; cannot distinguish mismatch direction
3	929.894	0.39	1414.799	0.872	Partially interpretable but merges distinct mismatch states
4	699.011	0.372	1407.981	0.879	Best theoretical correspondence with four mismatch configurations
5	558.543	0.369	1408.706	0.81	More fragmented; no additional clear theoretical type
6	464.888	0.367	1409.281	0.839	More fragmented; reduced parsimony

Note: SSE = sum of squared errors. Silhouette, Calinski-Harabasz, and Davies-Bouldin are clustering validation indices. The final clustering solution was determined by considering both statistical indicators and theoretical correspondence with the proposed health literacy-activity behavior mismatch framework.

Table 6. Clustering results of health literacy-activity behavior mismatch groups.

	BDG	HHG	LDG	LLG
B_index	0.29	0.63	−0.55	−1.10
L_index	−0.26	0.84	0.03	−1.57
Number of cases	413	443	371	177
Percentage (%)	29.42	31.55	26.42	12.61

3.2. Differences in Street Environmental Response Trajectories Among Mismatch Groups

The two-factor model results (Table 7) showed that the group main effects were generally significant for behavioral motivation, cognitive ability, participation willingness, and mismatch-related indicators, with relatively high partial η^2 values. This indicates clear differences among the four mismatch groups in health literacy and literacy-behavior relationships. Since the groups were defined using the health literacy and activity behavior indices, this section focuses on the “environmental quartile $\times$ group type” interactions and response trajectories rather than re-testing baseline group differences.

The interaction effects showed differentiated patterns across the four street environmental dimensions (Figure 5). For slow-mobility space, the interaction effects on participation willingness, the mismatch index, and the absolute mismatch index were significant, whereas the interaction effect on cognitive ability was not, indicating that this dimension was more evidently associated with activity participation-related responses. Natural aes-

thetics showed the opposite pattern, with a significant interaction effect on cognitive ability but not on participation willingness, suggesting differentiated responses mainly at the level of environmental perception and cognitive evaluation. Activity facilities showed significant interaction effects on cognitive ability, participation willingness, and mismatch-related indicators, especially the absolute mismatch index. By contrast, service function showed weaker interaction effects, mainly reflected in the absolute mismatch index. Given the relatively small partial η^2 values of several significant interaction terms, the following interpretations focus on the direction and relative pattern of group responses rather than the magnitude of effects.

Table 7. Two-factor model results for outcome variables across street environmental dimensions.

Environmental Dimension	Outcome Variable	Group		Environment $\times$ Group	
		<i>p</i> -Value	Partial η^2	<i>p</i> -Value	Partial η^2
Slow-mobility Space	BM	<0.001	0.556	0.019	0.014
	CA	<0.001	0.421	0.14	0.010
	PI	<0.001	0.353	<0.001	0.020
	Mismatch Difference	<0.001	0.405	<0.001	0.020
	Absolute Mismatch Index	0.009	0.008	<0.001	0.027
Service Function	BM	<0.001	0.584	0.317	0.007
	CA	<0.001	0.457	0.561	0.006
	PI	<0.001	0.421	0.409	0.007
	Mismatch Difference	<0.001	0.417	0.263	0.008
	Absolute Mismatch Index	0.027	0.007	<0.001	0.024
Natural Aesthetics	BM	<0.001	0.565	0.003	0.018
	CA	<0.001	0.434	<0.001	0.021
	PI	<0.001	0.373	0.956	0.002
	Mismatch Difference	<0.001	0.410	0.007	0.016
	Absolute Mismatch Index	0.003	0.010	0.002	0.018
Activity Facilities	BM	<0.001	0.585	0.236	0.008
	CA	<0.001	0.462	0.013	0.015
	PI	<0.001	0.419	0.008	0.016
	Mismatch Difference	<0.001	0.415	<0.001	0.021
	Absolute Mismatch Index	0.072	0.005	<0.001	0.034

Note: BM stands for behavioral motivation, CA stands for cognitive ability, and PI stands for participation willingness.

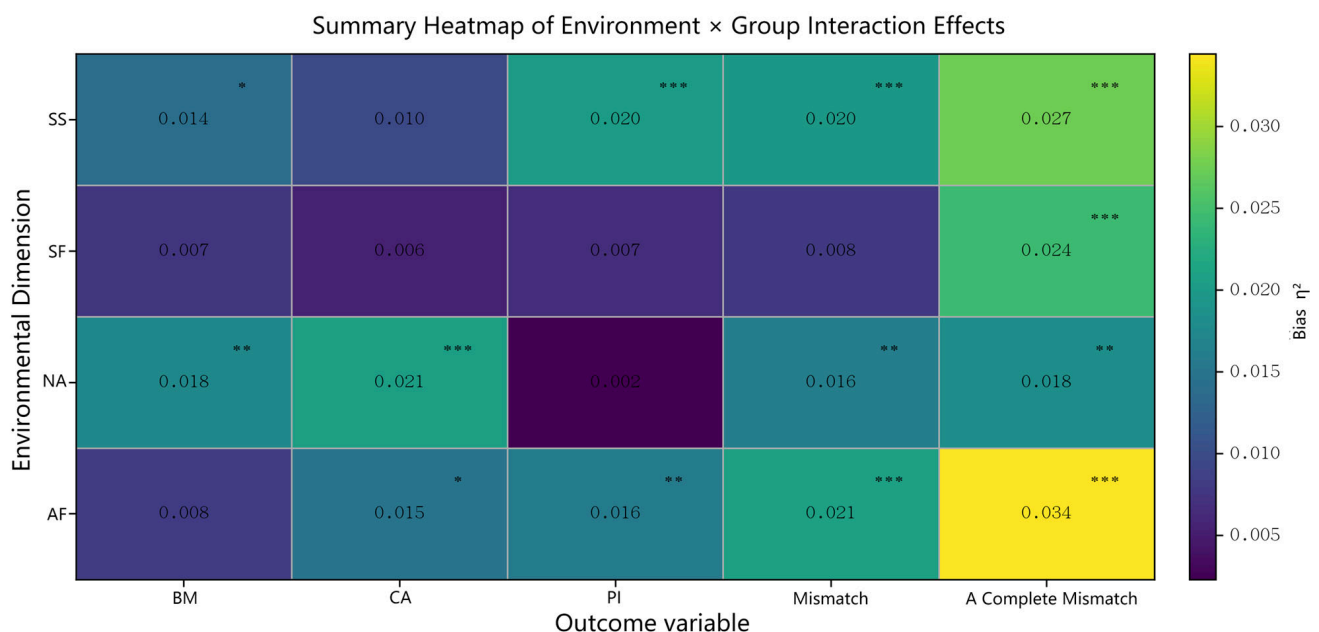


Figure 5. Heatmap of Environment $\times$ Group Interaction Effects.

The EMMs trajectory plots (Figure 6) further showed that behavioral motivation, cognitive ability, and participation willingness responded differently to environmental gradients. Participation willingness was relatively more sensitive to changes in environmental quartiles; behavioral motivation fluctuated less and mainly reflected stable between-group hierarchies; and cognitive ability fell between the two, showing gradual upward trends under some environmental dimensions. When the mismatch index and absolute mismatch index were considered together, higher perceived street environmental quality was associated with differentiated adjustments between literacy-leading and behavior-leading patterns, rather than a simultaneous convergence of all groups.

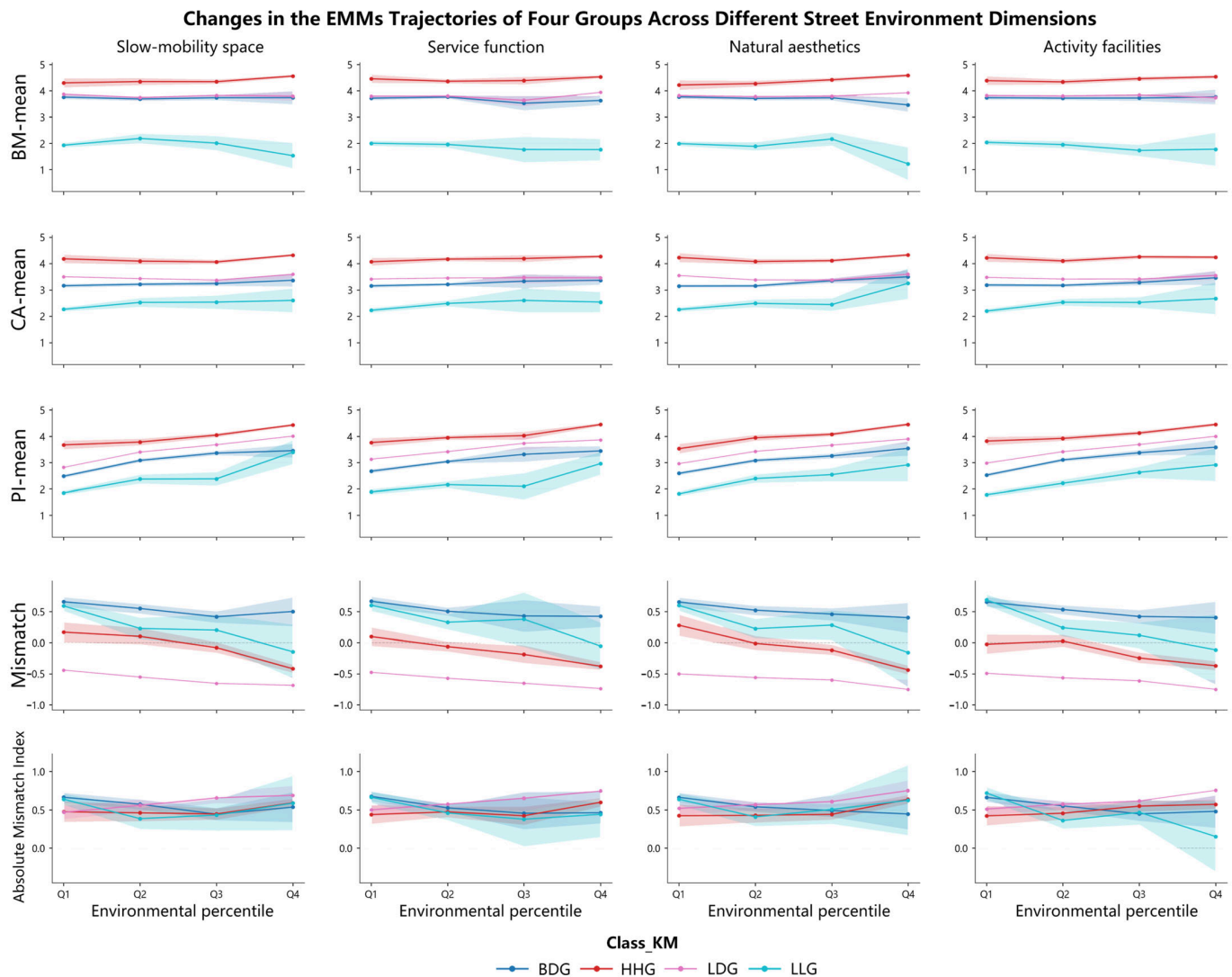


Figure 6. EMMs Trajectory Changes for Four Groups Across Different Street Environment Dimensions.

Specifically, slow-mobility space was mainly associated with differences in participation willingness and mismatch-related indicators. As slow-mobility space improved, HHG maintained relatively high levels of behavioral motivation, cognitive ability, and participation willingness, while LLG showed a more noticeable increase in participation willingness. In terms of mismatch relationships, LLG shifted from a clear positive mismatch to a slight negative mismatch in the higher quartiles, suggesting a change from a behavior-leading pattern toward a literacy-leading pattern. Meanwhile, its absolute mismatch index showed a certain contraction. This pattern indicates that slow-mobility space was associated with changes in the literacy–behavior relationship among LLG.

Service function showed relatively limited differentiation in group response trajectories. Although the mismatch direction of the four groups changed to some extent as service function improved, the overall pattern did not indicate strong group differentiation. Its significant interaction was mainly observed in the absolute mismatch index: BDG showed a continuous decline from Q1 to Q4, LLG declined more clearly in the low-to-middle quartiles, whereas HHG and LDG increased gradually. Overall, service function was associated with some changes in the degree of mismatch, but its role in differentiating group trajectories appeared relatively limited.

Natural aesthetics was mainly related to cognitive and perceptual changes. As natural aesthetics increased from lower to higher quartiles, cognitive ability and participation willingness generally increased across the four groups, with a particularly clear increase in cognitive ability among LLG. This suggests that natural aesthetics was associated with residents' perception, evaluation, and psychological acceptance of street environments, while its relationship with activity behavior appeared relatively indirect. In terms of mismatch relationships, some groups shifted from positive or nearly neutral mismatch toward negative mismatch as natural aesthetics improved, indicating that literacy-related changes may have been more evident than behavioral follow-up. Regarding the absolute mismatch index, BDG declined continuously, whereas HHG, LDG, and LLG showed varying degrees of increase or fluctuation. This suggests that natural aesthetics was associated with literacy-related changes, but the corresponding behavioral patterns varied across groups.

Compared with the other dimensions, activity facilities were more clearly associated with trajectory changes in LLG. As activity facilities improved, LLG showed relatively large changes in both health literacy-related and mismatch-related indicators. Its absolute mismatch index declined from Q1 to Q2, increased slightly at Q3, and then declined again at Q4, indicating a shift from a behavior-leading pattern to a literacy-leading pattern accompanied by a contraction in the absolute gap. This suggests that higher levels of activity facilities were associated with a closer relationship between health literacy and activity behavior among LLG.

Overall, different street environmental dimensions showed differentiated associations with the health literacy and activity behavior relationships of the four mismatch groups. Slow-mobility space was more closely associated with participation willingness and mismatch-related changes; natural aesthetics was mainly related to cognitive evaluation and perceived attractiveness; service function showed relatively limited group differentiation; and activity facilities were more clearly associated with changes in LLG. These findings indicate that perceived street environments are related to group-specific differences in health-promoting status, but the practical significance of small interaction effect sizes should be interpreted with caution.

3.3. Average Marginal Effects of Street Environmental Dimensions on Group Structure

To further examine the relationship between street environmental dimensions and changes in group structure from the perspective of group membership probabilities, this study used average marginal effects (AME) and Q1–Q4 predicted probability stacked charts. Unlike the EMMs trajectory analysis presented above, AME estimates the model-predicted average change in the probability of belonging to each mismatch group associated with a one-standard-deviation increase in a given environmental dimension, thereby comparing the relative associations between street environmental dimensions and model-predicted group structure.

The AME results (Table 8) showed that, after controlling for socio-demographic variables, a one-standard-deviation increase in each of the four street environmental dimensions was associated with an increase in the predicted probability of belonging to HHG, while the predicted probabilities of belonging to BDG, LDG, and LLG all decreased. Among the four dimensions, slow-mobility space showed the largest marginal change. For each one-standard-deviation increase in slow-mobility space, the predicted probability of HHG increased by 17.57 percentage points, whereas those of BDG, LDG, and LLG decreased by 8.01, 2.59, and 6.96 percentage points, respectively. The marginal effects of service function and natural aesthetics were relatively similar, increasing the predicted probability of HHG by 14.05 and 14.12 percentage points, respectively. By comparison, activity facilities showed a relatively smaller overall marginal change, increasing the predicted probability of HHG by 12.18 percentage points. Overall, higher evaluations of street environmental quality were consistently associated with a higher model-predicted probability of belonging to HHG.

Table 8. Analysis Table of AME Results for Four Environmental Dimensions.

Environmental Dimension	ΔP (BDG)	ΔP (HHG)	ΔP (LDG)	ΔP (LLG)
slow-mobility space	−8.0139	17.5666	−2.5916	−6.9611
service function	−7.1349	14.0508	−2.4868	−4.4291
natural aesthetics	−6.7581	14.1179	−2.9747	−4.385
activity facilities	−5.9447	12.1765	−2.4042	−3.8277

Note: ΔP represents the average change in probability, expressed in percent.

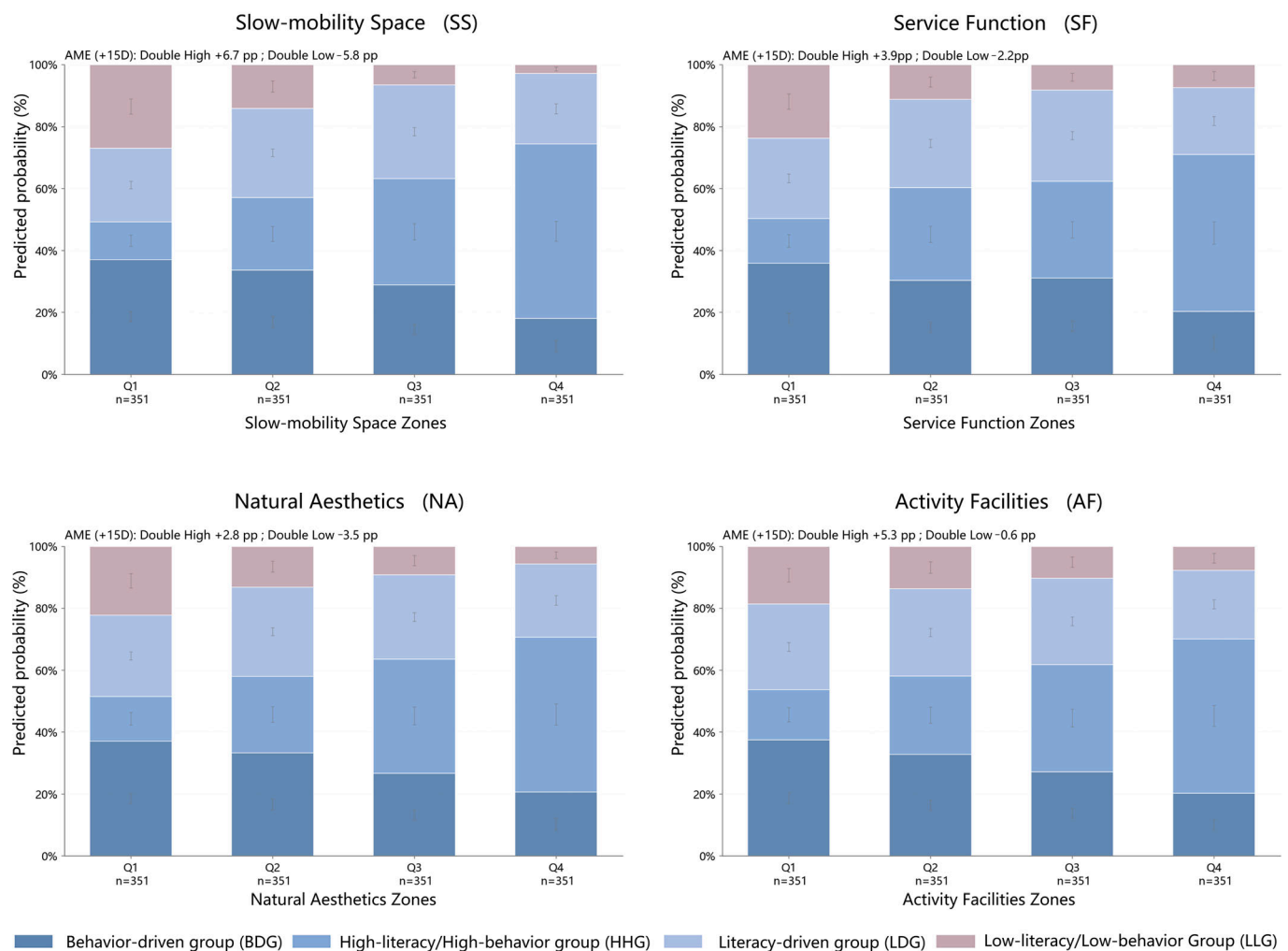
The Q1–Q4 predicted probability stacked charts (Figure 7) further showed that the four environmental dimensions were associated with broadly similar but differently scaled patterns of group-structure change. Slow-mobility space displayed the most pronounced model-predicted change. As slow-mobility space increased from the lowest to the highest quartile, the predicted proportion of HHG increased from 12.4% to 51.3%, a rise of 38.9 percentage points, while that of LLG decreased from 24.4% to 3.2%, a decline of 21.1 percentage points. LDG reached a local peak of 28.9% at Q2 and then declined to 25.0% at Q4. These results suggest that higher levels of slow-mobility space were associated with a higher model-predicted probability of HHG membership and a lower model-predicted probability of LLG membership.

The predicted probability patterns of service function and natural aesthetics were similar to those of slow-mobility space, but their overall magnitudes were relatively smaller. Notably, natural aesthetics showed a relatively clear decline in the predicted probability of LDG, while the predicted probability of HHG increased correspondingly. This indicates that higher natural aesthetics was associated with a lower model-predicted probability of remaining in a literacy-leading but behavior-lagging state.

Compared with the above dimensions, activity facilities showed a relatively smaller overall marginal change in the AME results. When considered together with the EMMs results, activity facilities still showed some association with trajectory changes in LLG, especially in relation to the contraction of the absolute mismatch index. This pattern suggests that activity facilities may be more relevant to within-group trajectory differences than to large changes in predicted group proportions.

Overall, the AME and Q1–Q4 predicted probability results indicate that all four street environmental dimensions were associated with a shift in model-predicted group structure toward HHG, although the strength and form of these associations varied. Slow-mobility space showed the largest association with shifts in model-predicted group structure, followed by natural aesthetics and service function. Activity facilities were relatively weaker

in overall group proportion changes but were associated with trajectory differences within LLG. These results should be interpreted as model-based associative patterns rather than evidence of causal effects.



Note: Q1–Q4 represent environmental zones; error bars indicate the 95% confidence interval; the notes below each sub-figure show the average probability changes for the “double-high” and “double-low” groups under the AME (+1SD) model.

Figure 7. Four-Dimensional Q1–Q4 Probability Forecast Stacked Chart.

3.4. Differences in Street Environmental Improvement Preferences Among Mismatch Groups

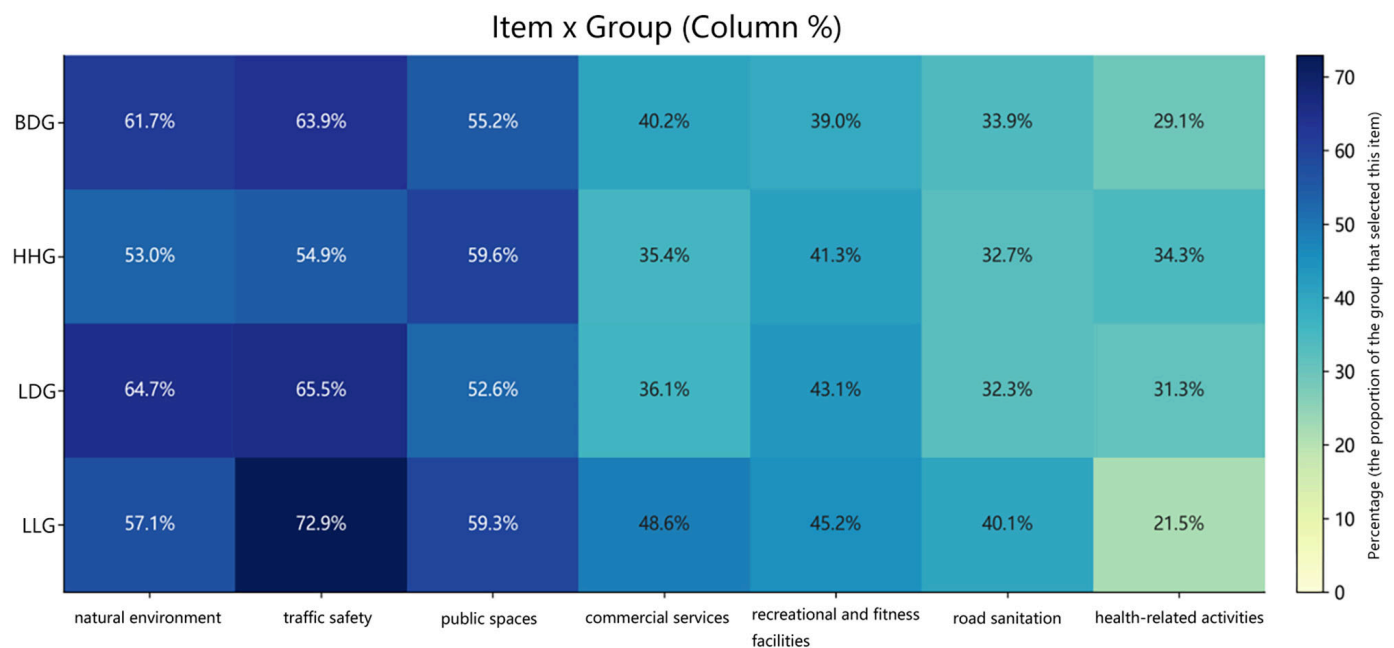
After identifying the environmental response trajectories and group-structure changes of the four mismatch groups, this study compared their priorities for street environmental improvements. The improvement items included seven categories: traffic safety, natural environment, commercial services, public activity spaces, road sanitation, recreational and fitness facilities, and health-related activities. Respondents could select multiple items. Selection rates were calculated within each group, and chi-square tests with Cramer’s V measured the strength of association. Pairwise comparisons were further conducted.

The overall results (Table 9) showed that preferences were mainly concentrated on basic environmental conditions. Traffic safety, natural environment, and public activity spaces had the highest selection rates, while road sanitation, recreational and fitness facilities, and health-related activities had lower selection rates.

Table 9. Multiple-response analysis results for street environmental improvement preferences.

Improvement Item	Number of Selections	Percentage of Cases (%)	Percentage of Responses (%)	<i>p</i> -Value	Cramer's V
Improving traffic safety	879	62.60	19.40	<0.001	0.122
Improving the natural environment	831	59.20	18.30	0.005	0.096
Improving public activity spaces	792	56.40	17.50	0.178	0.059
Improving recreational and fitness facilities	584	41.60	12.90	0.479	0.042
Improving commercial services	543	38.70	12.00	0.013	0.087
Improving road sanitation	476	33.90	10.50	0.293	0.051
Organizing health-related activities	426	30.30	9.40	0.016	0.086

From group profiles (Figure 8), all four groups shared some common preferences, but priority structures differed. BDG had higher selection rates for traffic safety and natural environment, with lower selection for health-related activities. HHG showed the highest selection rate for public activity spaces and relatively high selection for health-related activities. LDG showed higher selection rates for natural environment and traffic safety. LLG focused primarily on basic improvements, especially traffic safety, with relatively higher selection rates for commercial services, recreational and fitness facilities, and road sanitation.

**Figure 8.** Chart Showing the Proportion of Renovation Requests by Category.

Pairwise differences and association strengths (Figure 9) indicated that group differences were generally reflected in priority structures rather than completely distinct demand types. Cramer's V values ranged from 0.04 to 0.12, showing weak to moderate associations. After multiple-comparison correction, the more robust pairwise differences were concentrated in two items. LLG showed a significantly higher selection rate for traffic safety, and LDG showed a significantly higher selection rate for natural environment, indicating that these groups prioritized different aspects of basic environmental conditions. Overall, the four groups displayed different priority structures in their street environmental improvement preferences, reflecting distinct orientations rather than fully separate demand types.

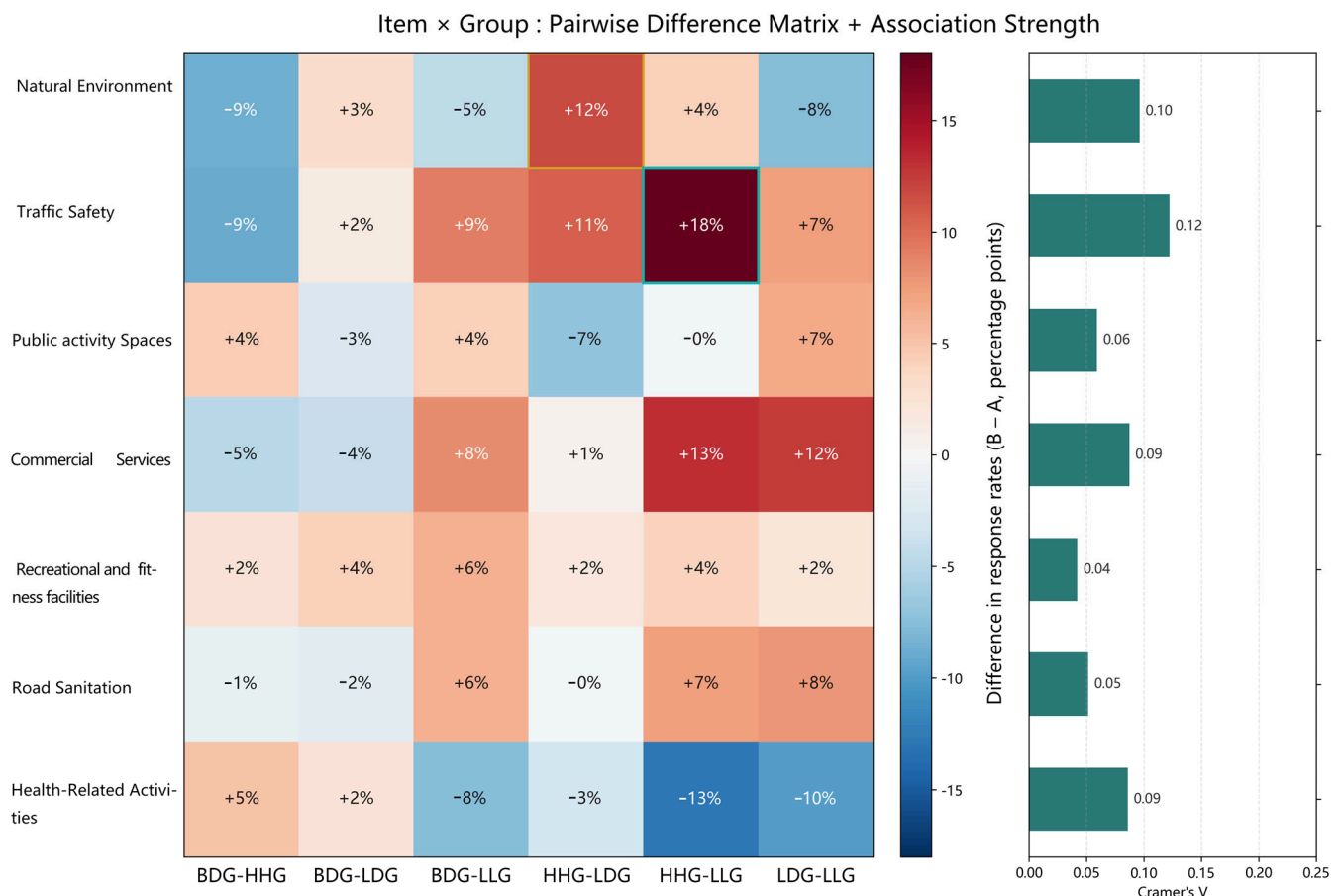


Figure 9. Pairwise Difference Matrix Among Groups Under Remodeling Requirements.

4. Discussion

The above results indicate that different mismatch groups showed differentiated patterns in street environmental responses and improvement preferences. These differences were related not only to the level of environmental evaluation, but also to the relative relationship between health literacy and activity behavior within each group. BDG, HHG, LDG, and LLG differed in whether activity behavior, health literacy, or both were relatively sufficient or insufficient, and these differences were reflected in their priority structures for street environmental improvement. Based on these results, this study proposes a hierarchical strategy for health-promoting street renewal in old urban neighborhoods that integrates basic support, literacy–behavior connection, and scenario enhancement (Figure 10). The purpose of this strategy is not to assign a fixed intervention package to each group, but to clarify how different environmental dimensions may correspond to different health-promoting needs and behavioral constraints.

First, basic safety should be prioritized. Traffic safety was the most frequently selected improvement item among residents. Slow-mobility continuity, pedestrian–vehicle separation, safety facilities, and nighttime lighting are basic preconditions for street-based activities. In old urban neighborhood renewal, slow-mobility space and traffic safety systems should therefore be treated as foundational intervention areas, especially for residents whose activity behavior and health literacy are both relatively low.

Second, environmental quality can be used to support the literacy–behavior connection. The results showed that natural aesthetics was associated with cognitive evaluation, participation willingness, and perceived attractiveness, especially among residents with relatively high health literacy but insufficient activity behavior. Therefore, renewal should

not remain limited to facility supplementation and road repair. Greater attention should be paid to greenery quality, streetscape interfaces, environmental cleanliness, and overall comfort, so that street environments may better correspond to residents' health cognition and willingness to participate in outdoor activities.

Schematic of Health-Promoting Street Renewal in an Old Urban Neighborhood

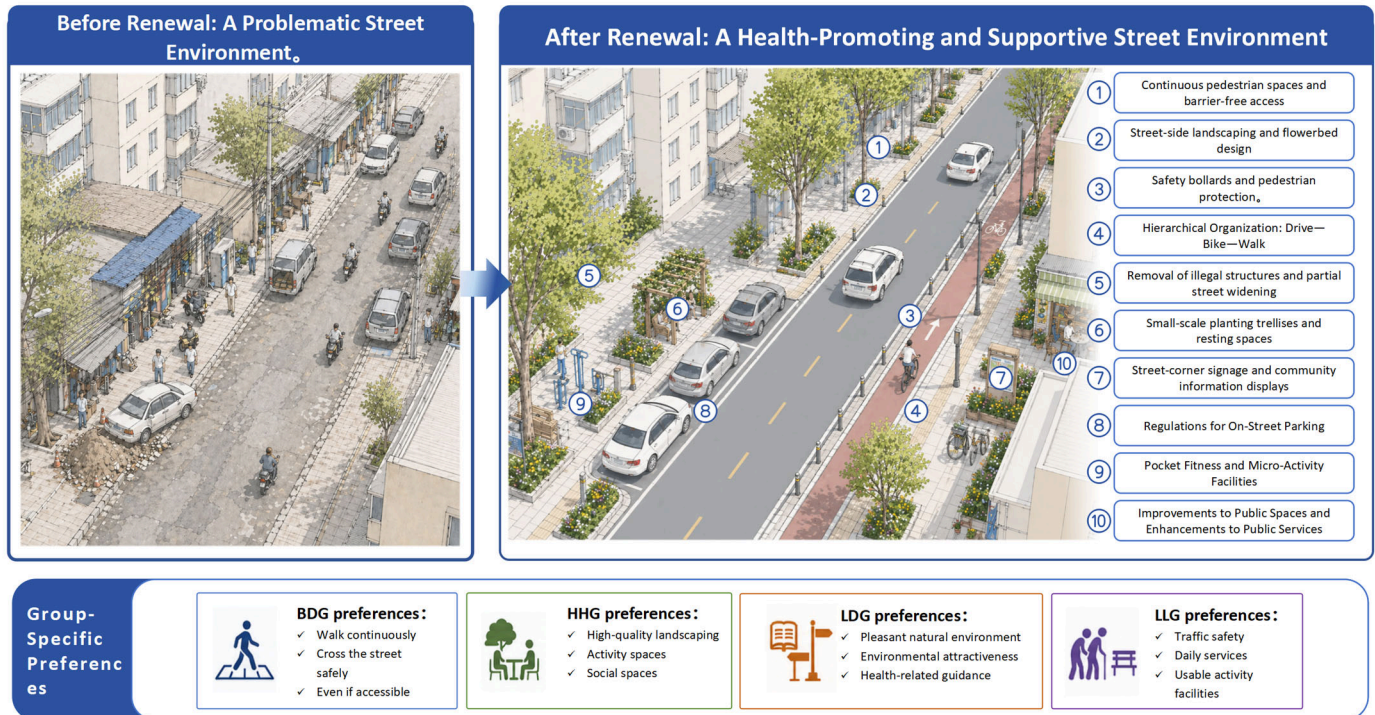


Figure 10. Strategy framework for health-promoting street renewal in old urban neighborhoods.

Third, the role of activity facilities in supporting activity engagement should be strengthened. Compared with other dimensions, activity facilities were more clearly associated with trajectory changes in LLG, especially in relation to the contraction of the absolute mismatch index. Therefore, the renewal of activity facilities should not be limited to increasing facility quantity, but should also improve the usability, accessibility, and diversity of spaces for staying, social interaction, exercise, and everyday leisure.

Finally, street renewal in old urban neighborhoods should move from single-item improvement to comprehensive optimization based on the behavioral chain. The health-supportive function of street environments is not determined by a single element, but is jointly shaped by slow-mobility accessibility, environmental perception quality, staying and activity conditions, and the usability of facilities and services. Based on the findings of this study, health-promoting street renewal can be summarized as a continuous support chain of “accessible–perceivable–stayable–usable”. In this chain, “accessible” emphasizes slow-mobility continuity and traffic safety; “perceivable” emphasizes natural aesthetics and environmental comfort; “stayable” emphasizes public activity spaces and places for staying; and “usable” emphasizes the practical usability of activity facilities and service functions.

Although these findings provide implications for street renewal, several limitations should be acknowledged. First, the sample was drawn solely from old urban neighborhoods within Jinan's Second Ring Road, limiting external validity. Second, AME and EMMs analyses are based on model-predicted probabilities and cross-sectional data; thus, results reflect associative patterns rather than causal effects. Third, street environmental evaluation relied primarily on residents' perceptions; objective measurements such as

greenery coverage, walkability, or connectivity were not included. Fourth, specific subgroups, such as older adults, children, or residents with limited mobility, were not further analyzed. Future research could include multiple cities, integrate objective environmental and behavioral measurements, conduct longitudinal or intervention studies, and perform subgroup analyses to improve generalizability and causal interpretability.

5. Conclusions

This study focused on residents in old urban neighborhoods of Jinan, China, and developed an analytical framework linking street environments, group differentiation, and renewal responses from the perspective of health literacy–activity behavior mismatch. It empirically examined differences in environmental responses and improvement preferences among different mismatch groups. The main conclusions are as follows.

First, residents exhibited clear health literacy–activity behavior mismatch characteristics and could be classified into four groups: BDG, HHG, LDG, and LLG, indicating heterogeneity in health-promoting status. Second, different street environmental dimensions were associated with different group response patterns. Slow-mobility space was mainly associated with participation willingness and mismatch-related changes; natural aesthetics was more related to cognitive evaluation and perceived attractiveness; activity facilities were more clearly associated with trajectory changes in LLG; and service function showed relatively limited group differentiation. Third, AME and predicted probability results showed that higher evaluations of street environmental quality were consistently associated with a higher model-predicted probability of belonging to HHG, with slow-mobility space showing the largest model-predicted association. Fourth, residents' improvement preferences were mainly concentrated on basic environmental conditions, with traffic safety, natural environment, and public activity spaces being the most prioritized items. Preference structures mainly reflected differences in improvement priorities rather than completely distinct demand types.

Overall, introducing the health literacy–activity behavior mismatch perspective into old neighborhood street renewal helps address limitations of traditional environmental evaluations that focus on physical space quality and average demand, linking resident heterogeneity with differentiated renewal responses. The findings should be interpreted as associative rather than causal. Future research should further test the framework across different urban contexts and integrate objective environmental measurements, longitudinal data, and subgroup analyses to improve generalizability and causal interpretability.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Participation in the questionnaire survey was voluntary, and all responses were collected anonymously. No personally identifiable information was recorded or used in this study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy considerations related to questionnaire respondents.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BDG	behavior-driven group
HHG	high-literacy/high-behavior group
LDG	literacy-driven group
LLG	low-literacy/low-behavior group

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