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# Effect of visual landscape factors on soundscape evaluation in old residential areas

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ABSTRACT

The visual landscape influences the soundscape experience of urban public spaces. The purpose of this study is to analyze the relationships among visual landscape factors and soundscape evaluation of old residential areas and determine their main influencing factors. In Tianjin, China, six typical old residential areas were selected to collect sound and video information. Virtual reality (VR) was used to create an evaluation environment, and subjective evaluations of the visual landscape and soundscape were accessed through questionnaire ($N = 256$). The results show that the evaluation of soundscape and visual landscape satisfaction of the central square in the old residential area is superior to that of the public space along the street, as affected by spatial location, sound characteristics and other factors. Greenery satisfaction, environmental cleanliness, and architectural aesthetics were significantly positively correlated with soundscape evaluation. Additionally, three latent variables, namely, visual landscape factors, spatial factors and soundscape evaluation factors, were identified through factor analysis, and a structural equation model (SEM) of "visual landscape factors–soundscape evaluation" was built. The visual landscape factors in old residential areas were found to be important factors affecting soundscape evaluation. The standardization coefficient was 0.46 ($P \leq 0.01$). Although the spatial factors have no direct contribution to the soundscape evaluation of the old residential areas, its observation variable, environmental cleanliness, is significantly positively correlated with all the observed variables of the soundscape evaluation factors.

## 1. Introduction

With the increasing urbanization rate, noise pollution in cities has become increasingly serious. It has been shown that high-density, crowded, and stressful urban environments can negatively impact residents' health because of factors such as air pollution and noise problems [1]. Continuous exposure to noise can lead to physiological and psychological discomfort in residents and increase the risk of hearing loss, insomnia, hypertension and other diseases over time [2]. Urban residential areas, as the main areas where residents live, are more sensitive to noise and are also areas with a high number of noise complaints from residents [3]. In 2020, China's environmental authorities received approximately 1,083,000 complaints about social living noise, accounting for 53.7 % of environmental noise complaints. After years of development, cities in China have entered the stock renewal stage, and nearly 170,000 old residential areas need to be renovated as of May 2020 [4]. Urban renewal provides a better opportunity to improve the acoustic environment of residential areas.

As an important part of the urban environment, soundscape means an acoustic environment as perceived or experienced and/or understood by a person or people, in context. (ISO 12913-1:2014) [5]. In the relevant research on soundscape perception, selecting appropriate acoustic indicators facilitates the understanding of the acoustic environment, such as loudness, annoyance, pleasantness and quietness [6]. However, people's perceptions of the acoustic environment are the result of the multisensory integrated effect, and merely reducing noise levels may not

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bring about a better acoustic environment and psychological experience [7]. Nonacoustic factors such as spatial form, landscape, physical environment and urban management are important factors affecting residents' perceptions of the acoustic environment [8].

In the urban environment, the spatial form is an important indicator affecting soundscape evaluation [9]. The street width-to-height ratio, average number of building stories, building density and building interval are all closely related to soundscape perception [10–12]. The appropriate spatial form can increase the comfort of the soundscape and reduce the negative impact of noise. Audio-visual consistency across spaces of the settlement is the key to perceiving the pleasantness and appropriateness of the sound [13]. For example, road visibility is negatively correlated with soundscape perception [14], reducing the pleasantness and suitability of water sounds when water is visually absent, and the perception of bird calls is not affected by visibility due to vegetation. Furthermore, a series of studies have focused on the relationship between landscape (green plants, the proportion of buildings, vegetation and sky, green landscape index, etc.) and soundscape perception in various types of spaces [15–17]. Color exposure, spatial interaction and inclusiveness in cities are also closely related to soundscape perception [18,19]. Although the above studies explored the relationships among various nonacoustic factors and soundscape evaluation in urban public spaces, there has been no systematic or comprehensive research on the effect of visual landscape factors on soundscape evaluation in urban old residential areas.

The interaction between soundscape evaluation and landscape is intricate, so various perceptual models have been proposed to predict soundscape perception in urban environments [20]. For example, structural equation modeling (SEM) was applied to examine the relationships among the various factors affecting the sound landscape and landscape perception or the indirect effects through latent variables (pleasantness, emotion, etc.) [21,22]. Zhao et al. established a structural equation model for the influence of urban environmental factors on soundscapes and found that the positive influence of urban management had the most significant positive influence on the dimension of pleasure, and the physical environment was positively correlated with the dimension of pleasure [23].

In China, the old residential areas are mainly residential areas built before the end of 2000, mainly multistory buildings, with high building density, relatively harsh environmental conditions, damaged and aging supporting facilities in the residential areas, and strong willingness of residents to transform. At present, China has a large stock of old residential areas, and the situation is complex. Promoting the reconstruction of old urban residential areas is an important measure to improve residents' living conditions and expand domestic demand. It is also a necessary measure to build a livable city and meet the spiritual needs of residents. Therefore, the old residential areas referenced here were built before the end of 2000 in 6 districts in Tianjin, with dilapidated buildings, a lack of activity space and a decline in the landscape environment, which make it difficult to meet the physical and psychological needs of residents and are in urgent need of renewal and transformation.

To improve the acoustic environment and residents' experiences in old residential areas, this study focused on the following issues: (1) exploring the soundscape characteristics of public spaces in old residential areas, (2) analyzing the effect of visual landscape factors on soundscape evaluation in old residential areas, and (3) utilizing a structural equation model (SEM) to extract the main factors influencing soundscape evaluation and proposing renovation and optimization strategies for the main influencing factors.

## 2. Methods

### 2.1. Study residential areas

The construction of urban residential areas in China began in the 1950 s and grew rapidly from the 1980 s to the 1990 s. These residential areas are mostly of a single residential function, with a construction scale of approximately 10 ha [24]. As time went by, they began to suffer from house dilapidation, environmental decay, aging facilities and insufficient activity space.

Tianjin, the largest coastal city in northern China, has many residential areas built before 2000 with a wide distribution, especially in the central area, where old residential areas account for more than 50 % of the residential land area. The scales of residential area lands are mostly between 3 and 15 ha, gradually increasing from the city center outwards, with plot ratios between 1.2 and 3.0, showing a gradient-descent trend from the center outward [25].

Six representative residential areas in six central urban districts of Tianjin were selected as the subjects in this study (Fig. 1). These residential areas were built before 2000, with a land area of 3.0–8.0 ha, a plot ratio of 1.2–2.4, and a building density of 20 %–40 %. The buildings are mainly multistory in a row or enclosure layout (Table 1).

### 2.2. Scene selection and Auditory-Visual information collection

According to the field survey, public activity spaces in old residential areas are mostly located in the center of residential areas or arranged along streets. As shown in Table 2, six typical public spaces (R1-R6) within the sampled residential areas were selected as the subjects in this study, of which R1-R3 were the central squares of the residential areas and R4-R6 were the public spaces along the streets of the residential areas. The survey found that the daily utilization rate of R1-3 was high, and there were common problems in old residential areas, such as dilapidated building facades, poor greening quality and serious hard space. The sound source type was mainly verbal conversation sound. R4-6 had problems such as a small footprint, lack of greening, space occupied by motor vehicles, and more traffic noise.

Sound and video information was collected from each residential area in December 2020 during two peak hours of crowd activity: 9:00–12:00 and 14:00–17:00. The visual landscape was recorded using GoPro Max, and panoramic video was recorded at 60 Mbps in 5.6 K Ultra

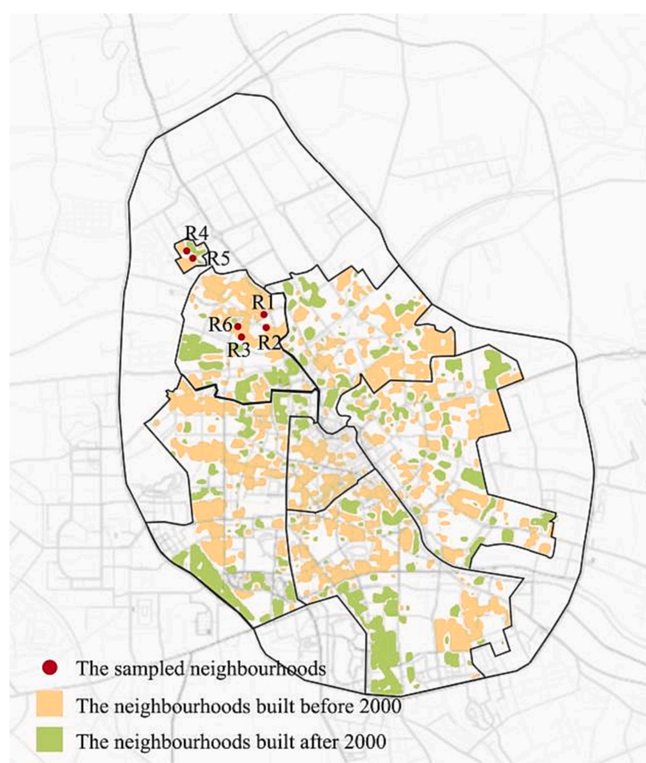
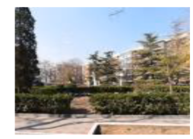



**Fig. 1.** The location of the sampled residential areas [26].

**Table 1**
Basic information of the sampled residential areas.

| The name of neighbourhood | Space features | | | | | Field photos |
|---|---|---|---|---|---|---|
| | Building construction age | Land area ( ha ) | Plot ratio | Building density | Average number of layers | |
| Fengguangli | 1995 | 3.7 | 2.3 | 37.63 % | 6.2 |  |
| QingchunNanli | 2000 | 3.1 | 1.6 | 36.45 % | 4.7 |  |
| Ziyali | 1987 | 8.1 | 1.7 | 29.65 % | 5.7 |  |
| JiayuanDongli (Southern) | 1999 | 5.2 | 1.7 | 30.65 % | 5.5 |  |
| JiayuanDongli (Eastern) | 1997 | 3.9 | 1.2 | 20.69 % | 5.8 |  |
| Dunhuanglou | 1988 | 4.6 | 1.5 | 23.44 % | 6.4 |  |

HD resolution and 30 fps resolution. During the data collection, the video were taken in good weather conditions with viewpoints at the same height, including various landscape factors such as sports facilities, natural vegetation, surrounding buildings and roads, with each recording lasting 8 min.

The sound was recorded in situ using the BHS II 3322 binaural microphone and headset paired with the SQobold 3302 4-channel recording and playback device (HEAD acoustics GmbH, Herzogenrath, Germany). Afterward, playback can also give the listeners an immersive experience of the original field of hearing. Its windproof cover is lightweight and removable, making it ideal for live recording. Meanwhile, sound pressure levels were measured using an HS5671B-type sound level meter for 5 min each time, ensuring that the instrument probe was 1.2–1.5 m from the ground and more than 1 m from the building facade. The sampling rate was 24-bit 44,100 Hz. The ICP binaural microphones and sound level meter have been calibrated by HS6020 calibrator (Frequency:1000 Hz, SPL:94 dB). For the psychoacoustic parameters of the recordings, the sound recorded by the BHS II Binaural headset was imported into SQobold SQP 01 FFT online analysis to calculate the psychoacoustic related parameters in accordance with ISO 532–1.

The acoustic and psychoacoustic indicators are shown in Table 3, For the SPLs from the binaural headset, using the left and right microphones to measure at six sites, Loudness and SPLs from binaural microphones at the first 5 min, synchronized with the sound level meter measuring the SPLs. The LAeq of the six sites measured by the sound level meter was distributed in the broad range of 53.7–67.5 dBA. LAeq was the lowest at Site R2 (central square) and the highest at Site R6 (roadside). The ICP binaural microphone measurements showed that A–weighted equivalent continuous sound pressure level LAeq,5min was distributed in 54.3–65.0 dBA. C–weighted equivalent continuous sound pressure level LCeq,5min, distributed in 58.5–73.6 dBC. And percentage exceedance levels LAF 5,5min and LAF 95,5min distribution ranged between 58.3 and 70.8dBA and 48.0–56.6dBA, respectively. For loudness, the ranges of loudness exceeded in 5 % of the time interval N5 and loudness exceeded in 95 % of the time interval N95 were 9.9–19.8 soneGF and 5.0–10.2 soneGF, respectively. Root mean cubed loudness Nrmc ranged from 7.6 to 14.5 soneGF.

To obtain the types of sound sources and residents' sound perceptions, residents moving around the site were randomly interviewed during the sound and video recordings. The respondents were asked to report the types of sound they heard (e.g., music from shops, mechanical noise, children laughing, wind, birdsong, traffic noise, and conversation). A 5-point Likert scale was applied to evaluate the perceived sound sources, with the following ratings: 1 = none at all, 2 = few, 3 = neutral,

**Table 2**
The public space scene of the sampled residential areas.

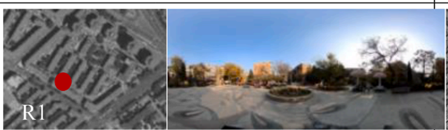
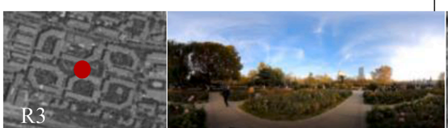
| Site | VR scenes | Site | VR scenes |
|---|---|---|---|
|   | |   | |
| Fengguangli | | JiayuanDongli (Southern) | |
|   | |   | |
| QingchunNanli | | Jiayuan Dongli(Eastern) | |
|   | |   | |
| Ziyali | | Dunhuanglou | |

**Table 3**
Acoustic and psychoacoustic indicators in 6 sites.

| Site | | R1 | R2 | R3 | R4 | R5 | R6 |
|---|---|---|---|---|---|---|---|
| LAeq,5min (dBA) | Sound level meter | 55.6 | 53.7 | 62.1 | 54.6 | 62.4 | 67.5 |
| LAeq,5min (dBA) | Left | 58.6 | 56.3 | 62.7 | 54.3 | 63.3 | 64.8 |
| | Right | 59.8 | 55.2 | 62.7 | 55.0 | 62.9 | 65.0 |
| LCeq,5min (dBC) | Left | 68.4 | 73.6 | 65.3 | 58.5 | 66.0 | 69.6 |
| | Right | 68.8 | 70.8 | 65.2 | 59.5 | 65.8 | 69.8 |
| LAF5,5min (dBA) | Left | 63.5 | 60.9 | 67.0 | 58.3 | 67.5 | 70.8 |
| | Right | 64.5 | 59.3 | 66.6 | 59.1 | 66.9 | 70.7 |
| LAF95,5min (dBA) | Left | 51.4 | 51.8 | 55.8 | 48.0 | 56.6 | 55.2 |
| | Right | 51.8 | 51.4 | 56.0 | 48.5 | 56.6 | 55.4 |
| N5 (soneGF) | Left | 17.1 | 13.7 | 18.8 | 9.9 | 16.3 | 19.3 |
| | Right | 18.6 | 13.0 | 18.1 | 10.9 | 16.2 | 19.8 |
| N95 (soneGF) | Left | 7.8 | 6.8 | 10.0 | 5.0 | 8.6 | 9.5 |
| | Right | 8.3 | 6.6 | 10.2 | 5.4 | 8.7 | 9.6 |
| Nrmc (soneGF) | Left | 11.8 | 9.6 | 14.3 | 7.6 | 12.6 | 14.3 |
| | Right | 12.7 | 9.1 | 14.1 | 8.3 | 12.5 | 14.5 |

4 = many, and 5 = complete.

### 2.3. Soundscape and Visual Landscape Perception Experiments.

#### 2.3.1. Experimental procedure

Referring to related studies, we did not collect 360 ambient sound using the microphone of GoPro Max because there may be interference due to hardware noise. Thus, a separate binaural microphone was used [27].

Before the start of the experiment, the recorded panoramic video was screened using GoPro Player, the interference frames were deleted during the operation of the device, and the correspondence and continuity of the experimental video and audio were ensured through editing. All videos were the same length. The edited video was decoded using GoPro Max Exporter for viewing via VR headsets, with the codec being HEVC with 4 K resolution.

Virtual reality (VR) technology can integrate multiple sources of information to achieve interactive 3D dynamic scenery perception and accommodate the physical movement of the experiencer. It has been shown that, except for real scenes, experimental scenes established by VR technology can provide subjects with a better sense of immersion and reality than ordinary videos and photos [28]. To better reproduce the real scenes, the subjects wore VR headsets (Type VIVE-VR) and HEAD acoustics 2019 binaural headphones to immerse themselves in the acoustic and visual scenes of public spaces in old residential areas. The HMD environment has a monocular resolution of 1080 × 1200 pixels (combined resolution of 2160 × 1200 pixels), dual AMOLED screen, 3.6 in., 90 Hz refresh rate, and 110° angle of view.

During the experiment, participants were allowed to rotate their heads or walk in a small range, thus allowing them to be truly immersed in the restorative environment constructed in the laboratory [22]. According to relevant studies [27,29], respondents evaluated overall soundscape quality, and the FOA-static binaural or dummy head-recorded binaural reproduction was sufficient. All experiments were performed in the same laboratory, where the background noise was very low, at approximately 27 dBA. To avoid individual adaptation differences and vertigo arising from prolonged use of VR headsets, the subjects' experimental time was controlled within 5 min. At the end of the experience, subjects filled out the Environmental Perception Questionnaire (Fig. 2). The experimental process and time control are shown in Fig. 3.

#### 2.3.2. Questionnaire

The Environmental Perception Questionnaire included 3 parts: individual characteristics of the subject, soundscape evaluation and visual landscape evaluation. Part 1 recorded the subject's basic information, such as gender, age and major. Part 2 collected information on soundscape evaluation from the subject. As shown in Table 4, with reference to ISO 12913-2 (2018) [30], the noise level, comfort and pleasantness of the soundscape were evaluated with three pairs of adjectives: noisy–-quiet, uncomfortable–comfortable, and annoying–pleasant, respectively [31,32], and the answers were given with a 5-point Likert scale. Part 3 collected information on landscape evaluation from the subjects. Based on the conclusions from the existing studies and the characteristics of public spaces in old residential areas [7,16,33], five parameters (greenery satisfaction, environmental cleanliness, architectural aesthetics, sky visibility and space openness) were selected to evaluate the visual landscape of public spaces in old residential areas and were rated with a 5-point Likert scale.

**Fig. 2.** Photos of the experiment site.

### 2.4. Participants

Participants to this study included both field survey respondents and laboratory respondents. A total of 165 residents active at the measurement site were randomly selected for this open interview. Among them, there were 103 males and 62 females; the largest group comprised retired middle-aged and elderly people aged 46 to 60, accounting for 43.64 %, followed by the group aged 61–75, accounting for 41.21 %.

A total of 200 college students were recruited to participate in the experiment, with a gender ratio of approximately 1:1, and all were majoring in urban and rural planning, architecture and design, etc. All subjects had normal hearing and visual acuity (including corrected visual acuity) and no color blindness. The students interviewed all have a good understanding of the characteristics of old residential areas, which ensures the accuracy of subjects' evaluations of old residential areas. During the experiment, 60 subjects participated in two groups of soundscape and visual perception experiments, but the second test was ensured one week after the first test to avoid interference with the results caused by the continuous test. The subjects agreed to be part of the study and completed the questionnaire after providing informed written consent. A total of 260 questionnaires were collected, four questionnaires were rejected because all the indicators were scored "5", resulting in poor reference and poor quality of the results, 256 of which were valid, for an effective rate of 98.46 %. Table 5 presents the statistics of the subjects' basic information.

### 2.5. Data analysis

The data collected from the experiments were entered into SPSS 23.0 for statistical analysis. One-way ANOVA was used to explore whether the perception differences of residents of different public spaces in old residential areas were significant. Prior to performing ANOVA, the data had already passed the normality test. Spearman's rho correlation analysis was used to analyze the relationships among visual landscape factors and soundscape evaluation in old residential areas. After performing reliability analyses and the Kaiser-Mayer-Olkin (KMO) test, a structural equation model (SEM) was chosen to explore the intrinsic relationships among residential visual landscape elements and soundscape evaluation. SEM belongs to multivariate statistics rather than analyzing only causal relationships among variables. SEM is a framework model for constructing, evaluating, and quantifying direct and indirect influences in causal networks, which allows for a clear analysis of the influence of single variables on the overall model as well as the interrelationships among variables.

The R system is widely used for statistics and calculation, where the

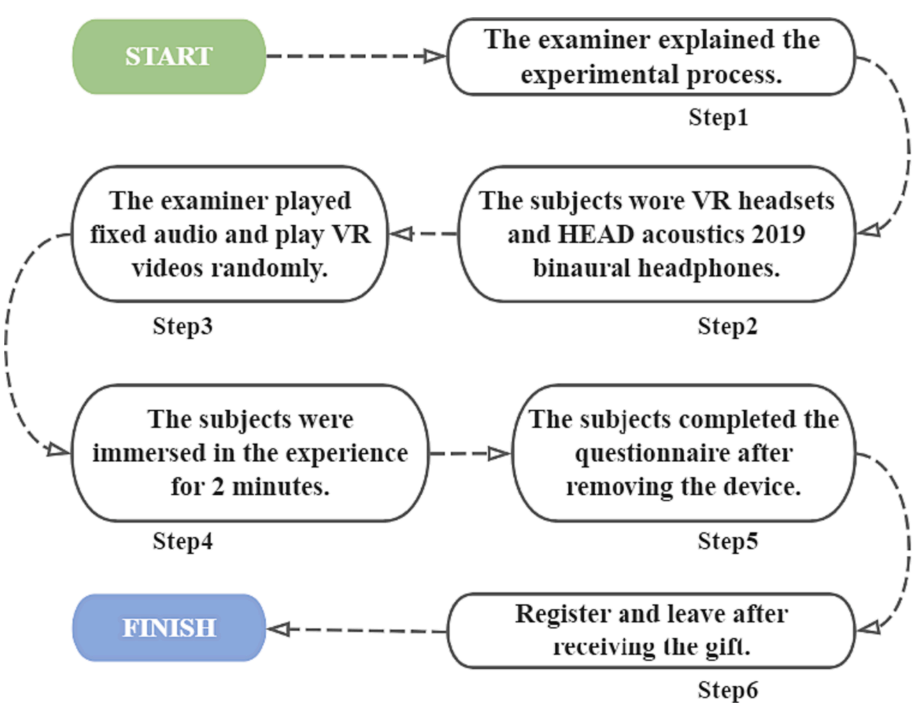



**Fig. 3.** Experimental procedures.

**Table 4**
Soundscape and visual landscape evaluation scales.

| Type | Evaluation dimension | | Very | Slightly | Neutral | Slightly | Very | |
|---|---|---|---|---|---|---|---|---|
| Soundscape evaluation factors | Noise level | Noisy | 1 | 2 | 3 | 4 | 5 | Quiet |
| | Comfort | Uncomfortable | 1 | 2 | 3 | 4 | 5 | Comfortable |
| | Pleasantness | Bad | 1 | 2 | 3 | 4 | 5 | Good |
| Visual landscape factors | Greenery satisfaction | Bad | 1 | 2 | 3 | 4 | 5 | Good |
| | Environmental cleanliness | Bad | 1 | 2 | 3 | 4 | 5 | Good |
| | Architectural aesthetics | Bad | 1 | 2 | 3 | 4 | 5 | Good |
| | Sky visibility | Bad | 1 | 2 | 3 | 4 | 5 | Good |
| | Space openness | Bad | 1 | 2 | 3 | 4 | 5 | Good |

**Table 5**
Basic information of the subjects.

| The central squares of the neighborhoods (N = 134) | | | The public spaces along the streets (N = 122) | | |
|---|---|---|---|---|---|
| Indicators | | Number of samples (%) | Indicators | | Number of samples (%) |
| Gender | Male | 63 (47.01 %) | Gender | Male | 60 (49.18 %) |
| | Female | 71 (52.99 %) | | Female | 62 (50.82 %) |
| Age | ≤20 | 72 (53.73 %) | Age | ≤20 | 74 (60.66 %) |
| | 21–25 | 57 (42.54 %) | | 21–25 | 47 (38.52 %) |
| | > 25 | 5 (3.73 %) | | > 25 | 1 (0.82 %) |
| Major | Urban and Rural Planning | 95 (70.90 %) | Major | Urban and Rural Planning | 87 (71.31 %) |
| | Architecture | 35 (26.12 %) | | Architecture | 32 (26.23 %) |
| | Design Science | 4 (2.98 %) | | Design Science | 3 (2.46 %) |

software package lavaan implements the construction of structural equation models. Lavaan is an acronym for latent variable analysis, which provides a range of tools to explore, estimate and understand a wide range of potential variable models, including factor analysis, structural equations, multilevel models, potential classes, project responses, and missing data models [34]. Therefore, in this study, the SEM was built with the lavaan package (v0.6.11; Rosseel 2012) in the R system (v4.2.0; R Core Team 2022) to analyze the mechanism of the effect of visual landscape factors on soundscape evaluation. To build the structural equation, reliability and validity tests and exploratory factor analysis (EFA) were first conducted on the subjects' soundscape and visual landscape evaluation results. Confirmatory factor analysis (CFA) was then conducted based on the results of the soundscape and visual landscape evaluation, and the maximum likelihood method was applied to evaluate the goodness-of-fit of the CFA. The SEM of "visual landscape factors–soundscape evaluation" was built after fit correction.

## 3. Results

### 3.1. Acoustic environment characteristics of public spaces in old residential areas

The sound pressure level statistics for the public spaces in the sampled residential areas are listed in Fig. 4. As shown in the figure, the equivalent sound pressure levels for the central squares of the residential areas (R1-R3) ranged from 53.7 to 62.1 dBA, with a mean value of 57.1 dBA. The equivalent sound pressure levels for the public spaces along the streets (R4-R6) ranged from 54.6 to 67.5 dBA, with a mean value of 61.5 dBA, approximately 4 dBA higher than that for the central squares. It was noted from the comparison between the sound pressure levels L90 and *L*10 that the mean L90 for the central square of the residential area was 47.7 dBA, while the mean L90 for the public space along the street was 53.4 dBA, approximately 5 dBA higher than that for the central square. The mean *L*10 for the central square of the residential area was 59.1 dBA, while the mean *L*10 for the public space along the street was 64.0 dBA, approximately 5 dBA higher than that for the central square.

The frequency statistics of sounds (rated as "4" and "5") heard by the respondents are described in Fig. 5, with the total frequency of sounds occurring in the central square of the residential area and in the public space along the street being 166 and 108 times, respectively. The most frequent sound heard in the central square of the residential area was conversation, which occurred 70 times in total, accounting for 42.17 % of the frequency of sounds heard, followed by traffic noise, which occurred 36 times, accounting for 21.69 % of the frequency. The least was store music. The most frequent sound heard in the public space along the street was traffic noise, which occurred 44 times, accounting for 40.74 % of the frequency of sounds heard. Conversation occurred 23 times, accounting for 31.30 %, and was the result of residents' conversations during exercise.

Fig. 6 displays the results of the soundscape evaluation for both types of spaces, including noise level, comfort, and pleasantness. As shown in the figure, the respondents tended to evaluate the noise level for both

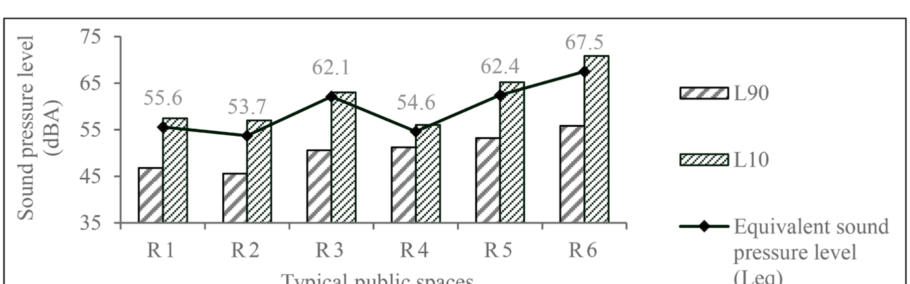



**Fig. 4.** The sound pressure level statistics for the public spaces in the sampled residential areas.

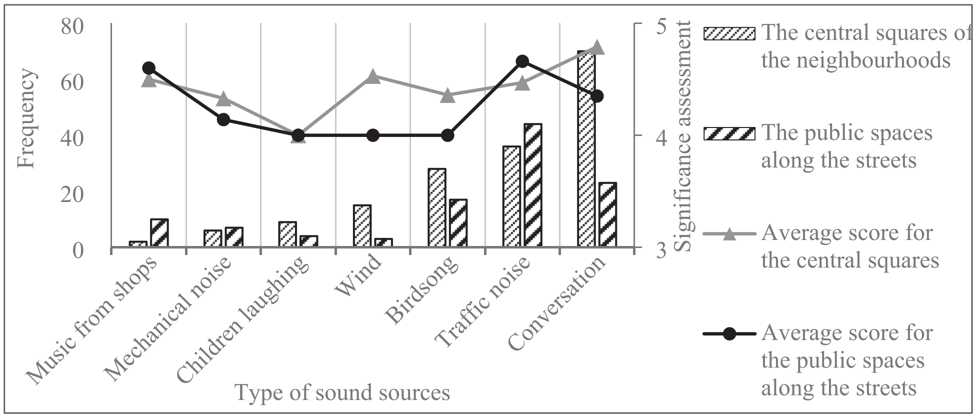



**Fig. 5.** The frequency statistics of sounds heard by the respondent.

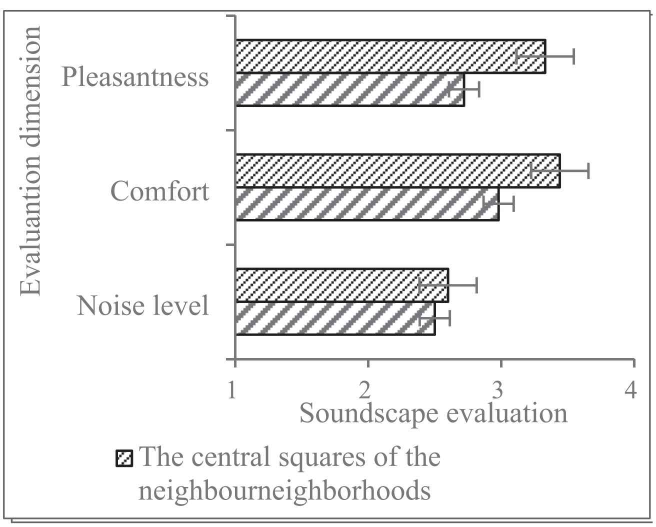



**Fig. 6.** Results of the soundscape evaluation.

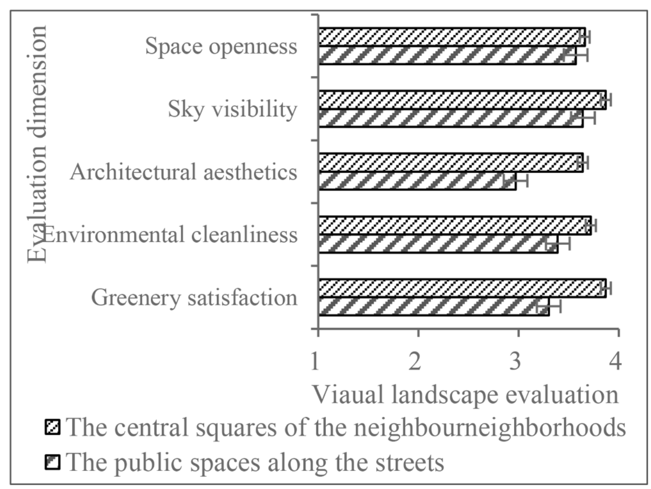



**Fig. 7.** Results of the visual landscape evaluation.

the central square and the public space along the street in old residential areas as "noisy", with means of 2.60 and 2.50, respectively, indicating a small difference. Unlike the noise level, the soundscape pleasantness and comfort scores for the central square of the residential area were 3.33 and 3.44, respectively, which were significantly higher than those (2.72 and 2.98) for the public space along the street. After conducting a one-way ANOVA, we further verified that there was no significant difference in the noise evaluation of the two types of spaces ($P = 0.384$), while there were significant differences in the evaluation of acoustic pleasure and comfort in various public spaces ($P < 0.01$).

The visual landscape evaluation for both types of spaces is presented in Fig. 7, including greenery satisfaction, environmental cleanliness, architectural aesthetics, sky visibility and space openness. In the central square of the residential area, the subjects evaluated five landscape factors as high, all above 3.50. In the public space along the street, the respondents evaluated greenery satisfaction and environmental cleanliness at the general level (3.30 and 3.39) and architectural aesthetics at the lower level (only 2.97). One-way ANOVA of the visual landscape evaluation showed that, except for sky visibility and space openness, the green satisfaction ($P < 0.01$), architectural aesthetics ($P < 0.01$), and environmental cleanliness ($P < 0.05$) evaluations of the two types of space were all significantly different.

### 3.2. Analysis of the relationship between soundscape and visual landscape evaluation

To analyze the effect of visual landscape factors on soundscape evaluation, a correlation analysis of visual landscape factors and soundscape evaluation was conducted, as shown in Table 6. The results showed that greenery satisfaction, environmental cleanliness and architectural aesthetics were significantly positively correlated with the evaluation of noise level, comfort and pleasantness. This means that an excellent visual landscape positively influences people's perception of soundscapes. Sky visibility and space openness were significantly positively correlated with only soundscape pleasantness. This indicates that spatial factors do not have a significant effect on noise level and comfort, but an open view can reduce people's annoyance with noise and increase the pleasantness of residents in public space.

### 3.3. Building of structural equation model for visual landscape Factors–Soundscape evaluation

#### 3.3.1. Exploratory factor analysis (EFA) of visual landscape factors and soundscape evaluation

SPSS 23.0 software was used to perform reliability analyses of soundscape evaluation factors (noise level, comfort, pleasantness) and visual landscape factors (greenery satisfaction, environmental cleanliness, architectural aesthetics, sky visibility and spatial openness). The results showed that the Cronbach's alpha coefficient was 0.749, with good internal consistency of the data and a high degree of confidence. In

**Table 6**
Correlations between visual landscape factors and soundscape evaluation.

| Satisfaction evaluation | Greenery satisfaction | Environmental cleanliness | Architectural aesthetics | Sky visibility | Space openness |
|---|---|---|---|---|---|
| Noise level | **0.170**** | **0.285**** | **0.139*** | 0.065 | 0.083 |
| Comfort | **0.230**** | **0.220**** | **0.226**** | 0.074 | 0.060 |
| Pleasantness | **0.257**** | **0.350**** | **0.270**** | **0.168**** | **0.149*** |

*. Correlation is significant at the 0.05 level;
**. Correlation is significant at the 0.01 level.

the element dimension of soundscape evaluation, the Cronbach's alpha coefficient was 0.757. In the visual landscape factors dimension, the Cronbach's alpha coefficient was 0.708, and the results show that the data of both dimensions have good consistency and high credibility. In addition, McDonald's omega coefficient was 0.820, higher than 0.8, indicating that the data were of high reliability and can be used for further analysis. The Kaiser-Mayer-Olkin (KMO) test returned a value of 0.719, which is greater than the threshold value of 0.70, and Bartlett's test yielded a significance level of $< 0.001$, which shows that the factor analysis was useful with the dataset [20]. In addition, this confirmed the possibility of modeling visual landscape perception and soundscape evaluation using SEM.

This study measured eight variables in the Environmental Perception Questionnaire, namely, noise level (S1), comfort (S2), pleasantness (S3), greenery satisfaction (X1), environmental cleanliness (X2), architectural aesthetics (X3), sky visibility (X4) and space openness (X5). SPSS 23.0 was adopted for principal component analysis, and the factor loading matrix was calculated to obtain the rotated principal component matrix through maximum variance analysis, as shown in Table 7 for the results. Three common factors were finally extracted, with a total explanation degree of 69.343 % (exceeding 60 % as a good explanation degree), which were summarized as visual landscape factors, spatial factors and soundscape evaluation factors.

### 3.3.2. Confirmatory factor analysis (CFA) for visual landscape factors and soundscape evaluation

The common factors obtained from the EFA results were used as latent variables, and the corresponding variables were used as observed variables to build the SEM of "visual landscape factors–soundscape evaluation" for old residential areas. To test the reliability of the model, CFA was carried out with lavaan in RStudio software. The results showed that the three groups of observed variables had strong internal correlation, indicating the reliable explanation degree of observed variables on latent variables. Parameter estimation was carried out with the maximum likelihood estimation method, with the P value (Chi-square), goodness-of-fit index (GFI), comparative fit index (CFI), root mean square error of approximation (RMSEA) and other parameter values as reference bases to judge the reasonableness of the model and to make corrections to the internal path of the model.

**Table 7**
Principal factors in the visual landscape and soundscape evaluation factors that were extracted via EFA.

| Number | Common factor | | Factor loading | Explained variance (%) |
|---|---|---|---|---|
| 1 | Visual landscape factors | Greenery satisfaction (X1) | 0.834 | 18.277 |
| | | Architectural aesthetics (X3) | 0.796 | |
| 2 | Spatial factors | Environmental cleanliness (X2) | 0.631 | 24.807 |
| | | Sky visibility (X4) | 0.881 | |
| | | Space openness (X5) | 0.859 | |
| 3 | Soundscape evaluation factors | Noise level (S1) | 0.737 | 26.259 |
| | | Comfort (S2) | 0.836 | |
| | | Pleasantness (S3) | 0.824 | |

According to relevant studies [10,35], visual landscape factors and spatial factors may affect soundscape evaluation, and there may be causal effects among variables. Therefore, M1 and M2 were used as the model hypothesis paths to complete the preliminary building of the SEM of "visual landscape factors–soundscape evaluation" for old residential areas. In the process of constructing the structural model, the modification index (MI) is an important parameter for the model adjustment. On the premise that the path logic is reasonable and the MI exceeds 4, we successively increased the corresponding path from high to low and conducted further model testing. For example, after constructing the two main hypotheses of M1 and M2, the path with a correlation between sky visibility and spatial openness had the largest MI value of 10.817, so this path was added first. Similarly, three paths were added between environmental cleanliness and noise level, pleasantness and comfort. Finally, the *meta*-model of the "visual landscape factors-sound landscape evaluation" for the old residential areas is shown in Fig. 8.

### 3.3.3. Fit correction of SEM

The parameters were estimated with the maximum likelihood estimation method on the basis of the preliminary structural equation. Based on the modification index (MI) values and $P(>|z|)$ values of the paths in the output results, the spatial factors → soundscape evaluation path (M2) in the metamodel was removed on the premise that the model logic was reasonable. The modified model was compared to the AIC and BIC values of the *meta*-model, and the smaller values represent a better model. The results showed that after path reduction, the AIC value decreased from 5193.7 to 5191.8, and the BIC value decreased from 5275.3 to 5269.8. The modified model fit indexes were further optimized, all paths were significantly correlated, and the model fit was improved (Table 8). This indicates that the modified model of the relationships among the factors influencing soundscape evaluation in old residential areas is more reasonable. Visual landscape factors (greenery satisfaction and architectural aesthetics) have a positive effect on soundscape evaluation in the public spaces of old residential areas.

### 3.3.4. Analysis of SEM of "Visual landscape Factors–Soundscape Evaluation"

The modified model is displayed in Fig. 9, and the results of the standardized path loadings of the SEM for visual landscape factors and soundscape evaluations are presented in Table 9. As shown in the figure, visual landscape factors had a significant effect on soundscape evaluation, with a standardized path coefficient of 0.46. Among the observed variables, architectural aesthetics with the maximum factor loading (0.71) was the main effect indicator, followed by greenery satisfaction (0.60). This indicates that architectural aesthetics contribute more to effective attention recovery in old residential areas and that improving building facades can promote more positive emotional generation than optimizing the natural landscape.

The spatial factors had no direct impact on the soundscape evaluation but had a significant positive correlation with the visual landscape factors ($P \leq 0.01$), and the standardized path coefficient was 0.56. In addition, the observed variable of spatial factors, environmental cleanliness, was significantly positively correlated with the observed variables of soundscape evaluation factors, noise level, comfort and pleasantness. Among them, the correlation between environmental cleanliness and soundscape pleasantness was the strongest, with a

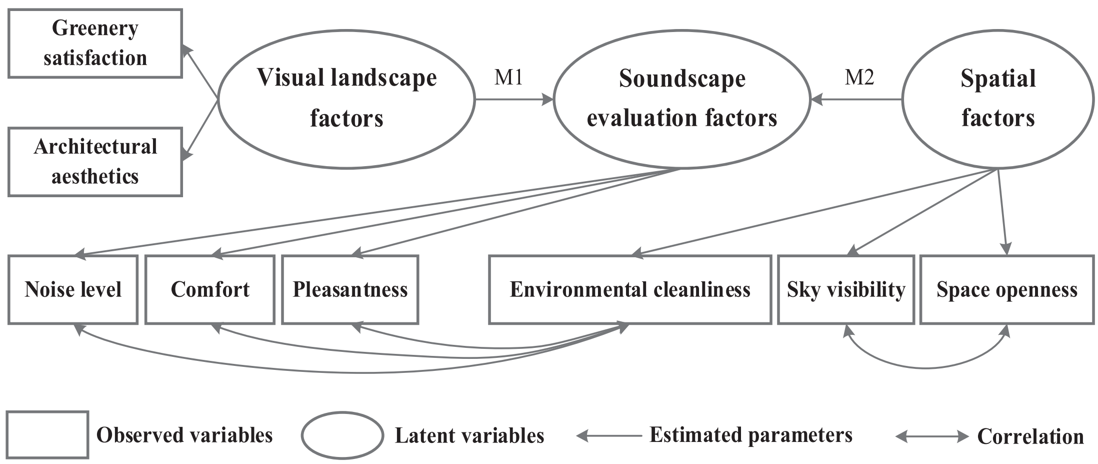



**Fig. 8.** Meta model of "Visual Landscape Factors–Soundscape Evaluation" for old residential areas.

**Table 8**
The values of goodness-of-fit indices for the meta and modified models.

| Model fit index | Recommended values | Initial values | Modified values |
|---|---|---|---|
| P-value | > 0.05 | 0.823 | 0.869 |
| GFI | > 0.90 | 0.992 | 0.992 |
| CFI | > 0.90 | 1.000 | 1.000 |
| RMSEA | < 0.08 | 0.000 | 0.000 |

standardized path coefficient of 0.46. This shows that although the spatial factors of old residential areas have no significant impact on soundscape evaluation, environmental cleanliness is still of great importance for soundscape evaluation.

## 4. Discussions

Reducing noise pollution is one problem that urgently needs to be solved in the renewal of old residential areas. Many studies have confirmed that the visual landscape has a significant impact on residents' perceptions of the acoustic environment [10,12]. This study comprehensively analyzed the relationship between the visual environment of the public space in old residential areas and soundscape evaluation and proposed an optimization strategy for the soundscape and visual landscape.

### *4.1. Effect of visual landscape factors on soundscape evaluation in old residential areas*

Residential squares are the main places for residents' outdoor activities, and the sound sources and sound pressure levels vary greatly depending on the location, scale and other factors. The central squares of residential areas are far from traffic-oriented roads, where residents mostly carry out leisure and recreational activities, and conversation is the dominant sound source. The public spaces along the streets are close to traffic-oriented roads, where traffic is the dominant sound source and the sound pressure levels are high.

The comparison of soundscape evaluation between the central square and the public space along the street in older residential areas by respondents revealed small differences in the noise level evaluation and large differences in the comfort and pleasantness evaluations. This was because the noise level evaluation was correlated with the sound pressure level [36], and the average equivalent sound pressure levels differed by 4 dBA; thus, the difference in noise level evaluation was not significant. The evaluation value of soundscape comfort and pleasantness of the central square in the residential area was significantly higher than that of the public space along the street, which showed that in addition to the sound pressure level, the visual landscape was of great significance for soundscape evaluation. This is consistent with the research results of Preis A et al., who found that the type and combination of visual landscape have a significant effect on improving

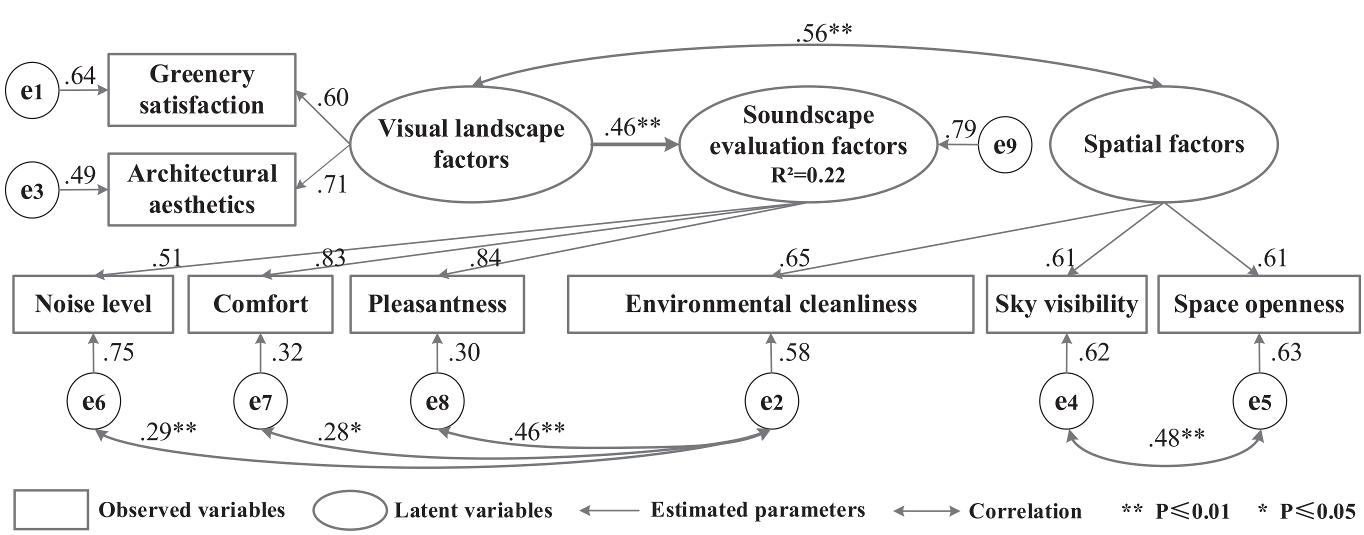



**Fig. 9.** Modified model of "Visual Landscape Factors–Soundscape Evaluation" for old residential areas.

**Table 9**
Standardized path loadings for the modified model of "Visual Landscape Factors–Soundscape Evaluation" for old residential areas.

| Path | Estimate | Standard Error | P(>\|z\|) | Standardized Coefficient |
|---|---|---|---|---|
| Visual landscape factors =~ Greenery satisfaction | 1.000 | – | – | 0.599 |
| Visual landscape factors =~ Architectural aesthetics | 1.210 | 0.233 | 0.000 | 0.712 |
| Spatial factors =~ Environmental cleanliness | 1.000 | – | – | 0.646 |
| Spatial factors =~ Sky visibility | 0.886 | 0.210 | 0.000 | 0.614 |
| Spatial factors =~ Space openness | 0.897 | 0.214 | 0.000 | 0.607 |
| Soundscape evaluation factors =~ Noise level | 1.000 | – | – | 0.505 |
| Soundscape evaluation factors =~ Comfort | 1.707 | 0.230 | 0.000 | 0.826 |
| Soundscape evaluation factors =~ Pleasantness | 1.607 | 0.217 | 0.000 | 0.836 |
| Soundscape evaluation factors ~ Visual landscape factors | 0.392 | 0.095 | 0.008 | 0.464 |
| Environmental cleanliness ~~ Noise level | 0.191 | 0.056 | 0.001 | 0.289 |
| Environmental cleanliness ~~ Comfort | 0.126 | 0.058 | 0.030 | 0.280 |
| Environmental cleanliness ~~ Pleasantness | 0.187 | 0.055 | 0.001 | 0.460 |
| Sky visibility ~~ Space openness | 0.292 | 0.092 | 0.001 | 0.476 |
| Visual landscape factors ~~ Spatial factors | 0.190 | 0.049 | 0.000 | 0.557 |

Note: table uses lavaan notation (=~: factor loadings; ~: regression paths; ~~: covariances).

soundscape comfort [37]. Comfort and pleasantness belong to the respondents' comprehensive feelings, closely linked with the sound source type of the place. The main noise source in the space along the street is traffic noise, and vehicles and roads are important reasons for the negative impact on the comfort and pleasantness of the soundscape [38]. This result supports the study of Nitidara et al., where the auditory aspect most significantly affected the overall comfort, and the higher the noise level in the environment was, the lower the overall comfort of the people [39]. Therefore, reducing the traffic noise of the nearby roads and beautifying the street landscape are conducive to enhancing the soundscape quality of the public space in the old residential areas [40].

This study concluded that greenery satisfaction, environmental cleanliness and architectural aesthetics in old residential areas are significantly positively correlated with soundscape evaluation. This is because people's perception of the environment is a multisensory experience, and the subjective preference of the visual environment affects auditory perception. In terms of greenery landscapes, green plants can enhance people's positive mood, thus reducing the negative impact of environmental noise through reasonable planting [41]. As far as the site environment is concerned, a proper community management system can keep the public space clean and tidy, thereby reducing the impact of noise and improving the soundscape experience [42]. Regarding residential buildings, the higher the decorativeness and aesthetic degree of the building facades around the public space in the old residential areas, the more positive the people's subjective feelings of the soundscape. This is similar to the research results of Shao Y et al., who concluded that in an environment where the sound pressure level is less than 77 dBA, visual aesthetics are significantly positively correlated with soundscape comfort [43]. Therefore, it is suggested to improve the visual aesthetics of the space environment during the renovation of the old residential areas, especially considering the subjective satisfaction of residents with the greenery landscape and building quality, and formulate a sound maintenance and management policy.

In this study, SEM was applied to analyze the relationships among visual landscape factors and soundscape evaluation in old residential areas. It was found that visual landscape factors had a direct impact on soundscape evaluation; in particular, the factor loading of architectural aesthetics as one of the observed variables was 0.71, which was higher than that of greenery satisfaction of 0.6. This is different from the conclusion that the greenery factor of urban public space contributes more significantly to soundscape perception evaluation than the artificial environment [43]. Therefore, in old residential areas, more attention should be given to the impact of artificial environments, such as the aesthetics and continuity of the building facade, on soundscape evaluation. Furthermore, spatial factors have no direct impact on the soundscape evaluation, but its observed variable, environmental cleanliness, has a significant positive correlation with the observed variables of the soundscape evaluation factors, noise level, comfort and pleasantness. Since the old residential areas are in disrepair for a long time and the sanitary environment is poor, it has a significant impact on the soundscape evaluation.

### 4.2. Soundscape optimization in old residential areas

The following suggestions for optimization are put forward in view of the low evaluation of the soundscape and architectural aesthetics for public spaces along the streets in old residential areas. First, multilayer greenery should be planted or noise barriers should be installed between urban roads and public spaces along streets to reduce the impact of traffic noise on residents' activities. Second, for the low evaluation of architectural aesthetics, the aesthetics of the building facade around the public activity space should be improved to create a good visual landscape. To improve soundscape pleasantness for public spaces, residential area renovation should optimize the continuity and width-to-height ratio of the architectural facade, increase space openness and create a more comfortable space for audio-visual experience. In addition, the conclusion that environmental cleanliness is positively correlated with the observed variables of soundscape evaluation also applies to the renovation of old residential areas, and emphasis should be placed on the maintenance and management of the public space environment during the renewal and renovation of old residential areas.

### 4.3. Limitations and further research

In this study, high-density residential areas in Tianjin were chosen as the subjects to derive the relationships among their visual landscape factors and soundscape evaluation. The applicability of the findings to low-density residential areas needs to be further investigated. In addition, all respondents in this study were college students, and their occupations and ages were relatively homogeneous; thus, future studies should be conducted on a wide range of age groups.

Moreover, the evaluation of the trial perception conducted in the laboratory relied on the paper version of the questionnaire. Despite the short duration of the experiment, the participants still needed to rely on memory to answer the questions, which may have biased the experimental results due to incomplete short memory or unimpressive memory. Therefore, future studies should explore the possibility of simultaneous experience and evaluation, thus reducing the experimental error.

This study focuses on the impact of the visual landscape on soundscape evaluation. In future studies, the comprehensive benefits and mechanism of the impact of visual landscapes and soundscapes on residents' psychology will be analyzed in depth for the purpose of improving the attention restoration and mental stress relief potential of the landscape environment in old residential areas.

## 5. Conclusions

In this study, the relationships among visual landscape factors and soundscape evaluation in public spaces of old residential areas were systematically analysed, and a structural equation model of the effect of visual landscape on soundscape evaluation was built, with the following conclusions:

First, the soundscape characteristics of public spaces in old residential areas in Tianjin were analysed. Sound pressure levels and major sound sources were influenced by the type and location of public spaces. Specifically, the equivalent sound pressure level of public spaces along the streets in old residential areas was approximately 4 dBA higher than that of the central square, and the main sound sources of the two types of spaces were traffic noise and conversation.

Second, the correlation between visual landscape satisfaction and soundscape evaluation in older residential areas was determined. Greenery satisfaction, architectural aesthetics, and environmental cleanliness were significantly positively correlated with soundscape evaluation, while sky visibility and space openness were positively correlated with only soundscape pleasantness.

Finally, a structural equation model of the effect of visual landscape factors on soundscape evaluation was built. According to the SEM, the visual landscape factors had a positive impact on the soundscape evaluation, and the environmental cleanliness of the residential area was significantly positively correlated with the noise level, comfort and pleasantness of the soundscape.

This study demonstrates that visual landscape factors in old residential areas are important nonacoustic indicators affecting soundscape evaluation, broadening the research perspective on the interaction between sound and visual landscapes and providing new ideas for the renewal and renovation of old residential areas.

## CRediT authorship contribution statement

**Zhiyu Zhou:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Xiaoqing Ye:** Conceptualization, Investigation, Methodology, Writing – original draft. **Junjie Chen:** Investigation, Analysis. **Xiaoyong Fan:** Investigation, Analysis. **Jian Kang:** Conceptualization, Methodology, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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