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Which Factors Enhance the Perceived Restorativeness of Streetscapes: Sound, Vision, or Their Combined Effects? Insights from Four Street Types in Nanjing, China

Xi Lu [1], Jiamin Xu [2], Eckart Lange [3,*] and Jingwen Cao [4,*]

[1] School of Landscape Architecture, Nanjing Forestry University, Nanjing 210037, China; luxi@njfu.edu.cn
[2] School of Design, Shanghai Jiao Tong University, Shanghai 200240, China; pekki-0816@sjtu.edu.cn
[3] School of Architecture and Landscape, The University of Sheffield, Sheffield S10 2TN, UK
[4] School of Architecture and Urban Planning, Nanjing University, Nanjing 210093, China
* Correspondence: e.lange@sheffield.ac.uk (E.L.); jw.cao@nju.edu.cn (J.C.)

Abstract: Streetscapes play a critical role in restorative landscapes, offering opportunities for promoting public well-being. Previous studies have predominantly examined the influence of visual and auditory stimuli on perceived restorativeness independently. There is a limited understanding of their interactive effects. In this research, 360 participants completed a series of experiments considering four distinct street types, including visual comfort assessment, acoustic environment assessment, and perceived restorativeness. They were assigned to a control group and one of three experimental groups, each receiving specific enhancement: visual stimuli, auditory stimuli, or a combination of audiovisual stimuli. The findings revealed that the experimental groups reported a greater sense of restorativeness compared to the control group. Notably, auditory stimuli demonstrated a more pronounced restorative effect than visual stimuli, while limited differences were found between auditory and audiovisual stimuli. The differences in experimental outcomes among the four street types are compared and discussed, highlighting context-specific guidelines for enhancing streetscape restorativeness. The research findings highlight enhancing the masking effect of soundscape in street environmental design. The study adds a novel multi-sensory approach to the current body of research on restorative landscapes, providing significant insights for the planning and design of streetscapes.

Keywords: streetscape; sound; vision; restorativeness; audiovisual interactions

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1. Introduction

Streets occupy approximately 25–35% of all developed urban land [1], representing a significantly larger portion of urban space compared to parks and other public areas. Given their integral role in the cityscape and their proximity to homes, streets serve as a primary location where residents spend a considerable amount of their outdoor time [2]. Streetscapes, encompassing both the physical and experiential components of streets, are an essential part of urban green infrastructure. They incorporate natural elements, including trees, shrubs, and water features, alongside human-made elements such as pavements and street furniture, to establish environments that are both visually appealing and functionally integrated. Within the broader concept of restorative landscapes—environments designed to promote psychological and physiological recovery—streetscapes have the potential to significantly enhance human well-being and alleviate stress [3]. A thoughtfully designed streetscape goes beyond merely addressing health and safety concerns; it also fosters the cultural identity of a community and stimulates economic growth and contributes to the visual image of sustainable cities, promoting tourism and overall urban success [4]. Despite their close connection to daily life and their potential impact on psychological well-being, streetscapes have not received significant attention in academic research concerning their restorative potential. This oversight has led to a lack of thorough guidelines for the effective design of streetscapes [5].

Existing research focusing on streetscape restorativeness has primarily focused on visual aspects [4,6], such as the green view index [7], green coverage [8,9] and street segmentation elements [10,11]. These visual elements are central to landscape planning and design, as they shape the aesthetic and functional qualities of urban spaces. Aside from visual effects, audition is a critical component of the five human senses. Soundscapes are increasingly recognized as a key factor in creating restorative environments [12]. The soundscape, which encompasses both natural sounds like bird calls and rustling leaves, as well as anthropogenic sounds such as traffic and conversations, provides a unique auditory experience that captures the essence of a place [13]. This auditory dimension, though sometimes subtle, can have a profound impact on our emotional reactions, eliciting a wide range of feelings from tranquility to discord [14]. However, few studies have combined auditory and visual perceptions to understand how people experience streetscapes [15].

Streets are categorized in various ways based on factors such as location, material, traffic, and function. For example, the US National Capital Planning Commission [16] distinguishes between radiating and edging streets, connecting and traversing streets, as well as local streets based on their geographical context. In terms of roadway functionality, the Federal Highway Administration (FHWA) [17] of the U.S. Department of Transportation (DOT) classifies roads into four main categories: interstates, other arterials, collectors, and local roads. Additionally, the *Nanjing Street Design Guidelines* categorize streets according to their relationship with surrounding land and buildings, identifying living streets, traffic streets, comprehensive streets, and service streets [18]. Previous research has largely focused on commercial streets [19] and living streets [20] in isolation. Only a limited number of studies on restorative environments have sought to evaluate the restorative potential of various street types [21].

Given the aforementioned research gaps, this study seeks to investigate the interaction effects of vision and sound on the perceived restorativeness of the streetscape, considering varied street types. Specifically, the aim is to examine the following two research questions:

Research Question I: Can vision and sound independently enhance restoration when considering different street types?

Research Question II: Can the combination of vision and sound enhance restorative effects compared to their independent roles, when considering different street types?

2. Literature Review

2.1. Restorative Landscape

"Restoration" refers to the process of regaining physical, psychological, and social abilities lost due to external environmental pressures [22]. This concept has been widely studied in the context of urban environments, where researchers have explored restorative potential from various perspectives, including housing, transportation, and—most notably—natural environments and urban green spaces. Restorative landscapes aim to foster psychological and physiological recovery by integrating multiple environmental dimensions [23,24]. These include natural, built, symbolic and social environments [24]. Theoretical developments in this domain have led to several frameworks that explain the factors influencing perceived restorativeness. Two prominent theories are the Attention Restoration Theory (ART), proposed by Kaplan et al. [25], and the Stress Reduction

Theory (SRT), posited by Ulrich et al. [26]. The former is a psycho-functionalist theory, emphasizing mental fatigue, while the latter is a psycho-evolutionary theory, focusing on physiological stress. Both theories share a common foundation: the idea that natural elements, such as greenery, water features, and open spaces, can significantly enhance human well-being by providing opportunities for mental and physical recovery [26,27].

The ART, in particular, delineates four crucial components of restorative environments: being away, fascination, extent, and compatibility [25]. These components are defined as follows: "Being away" refers to the psychological detachment from daily stressors and responsibilities, providing a mental break. "Fascination" indicates the ability of an environment to hold attention effortlessly. "Extent" relates to the quality of restorative environments that encourages one to feel totally immersed and engaged. "Compatibility" ensures that the environment aligns with the individual's goals and preferences, fostering a sense of belonging and ease.

Building on ART, Hartig [22] expanded the four dimensions of restorative environments by creating the Perceived Restorativeness Scale (PRS), which evaluates the restorative attributes of different settings and has been widely applied in natural, urban, and indoor contexts. Research endeavors grounded in the ART framework have predominantly centered on visual stimuli [28], often neglecting auditory components or failing to rigorously control for acoustic parameters. To address this gap, Payne [29] developed and validated the Perceived Restorativeness Soundscape Scale (PRSS). This scale, grounded in the four dimensions of ART, evaluates individuals' perceptions of a soundscape's capacity for psychological restoration. Collectively, these measurements provide a more comprehensive understanding of how both visual and auditory components influence the restorative qualities of urban environments.

2.2. Effects of Vision and Audition on Restorative Streetscape

Streetscapes, as a critical component of urban restorative environments, significantly influence human psychological restoration through differentiated activity patterns. Drawing upon Gehl's classification system [30], streetscape activities can be categorized into three dimensions: necessary, optional, and social activities. Necessary activities encompass obligatory routines such as commuting, work-related travel, and essential shopping, where environmental quality plays a relatively minor role in user engagement. Optional activities include utilitarian walking (e.g., combining shopping with café visits) and leisure-oriented strolling (e.g., walking children or pets). The third category, social activities, specifically involves interpersonal interactions and communal recreation. The latter two categories exhibit heightened sensitivity to environmental design attributes, serving as crucial mediators for sustaining public engagement and amplifying restorative effects through enhanced environmental design.

Emerging studies have shown that well-designed street environments can replenish psychological resources, reduce stress levels, and elicit beneficial physiological responses [31,32]. Within the environmental perception research paradigm that emphasizes the "environmental stimuli–perceptual feedback" framework, other related influencing factors are considered as contextual setting, with a greater focus on how individuals perceive, interpret, and respond to environmental stimuli through sensory mechanisms. To enhance these restorative benefits, scholarly discourse has predominantly focused on visual street design indicators, such as spatial morphology [33,34], functional aspect [35], specific street design elements [5,11], ecological sustainability [36], and identity-related factors [37,38].

For example, Lindal et al. [10] evaluated the presence of trees, flowers, and flower beds on humans' judgements of restoration likelihood. Jiang et al. [8], in an experiment involving video recordings of street foliage, showed a positive linear relationship between perceived stress and green coverage. More recently, Wu et al. [11] evaluated the impacts of different street elements (i.e., wall, tree, etc.) on restorative perception, combining street view images, deep learning, and space syntax. Additionally, Navarrete-Hernandez et al. [39] assessed the impact of levels and types of street greenery on people's perceptions of happiness using an image-based randomized controlled trial.

Beyond vision, the auditory environment also contributes significantly to restorative streetscapes. Research has identified two aspects of restoration related to perceived acoustic environments: (1) the direct positive influence of high-quality acoustic environments (e.g., natural sounds), and (2) the mitigating effect of access to such environments for individuals chronically exposed to noise pollution [40]. Epidemiological evidence regarding the intrinsic benefits of acoustically high-quality areas—such as green spaces, wilderness, or water—remains limited. Regarding the mediating role, quiet environments near residential areas can reduce noise annoyance and improve physiological outcomes like sleep quality and blood pressure. Furthermore, a temporary break from environmental noise may also counteract its adverse health effects [41]. The restorative potential of soundscapes is fundamentally shaped by the complex interplay of physical environmental characteristics. A notable investigation by Hong et al. [42] employed soundwalk methodology to investigate how urban functions influence the soundscape in streets, taking into account the relationships among human behaviors, the sound environment, and various acoustic indicators.

Controlled experiments further corroborate these findings. Exposure to natural sounds—whether in parks, urban areas, or virtual environments—consistently enhances mood, well-being, and perceived quality of life. For instance, Zhang [43] used a psychological scale to measure the restorative benefits of soundscapes by watching soundscape videos in a laboratory, while other studies examined the influence of sound on the perceptions of enclosures and restoration in urban street canyons with varying height-to-width ratios [44]. Collectively, this research underscores that urban soundscape, particularly in dense cities, profoundly influence individuals' restorative experiences.

A limited but growing body of research has examined the compounding effects of vision and sound on streetscapes [38]. For example, using images of streetscapes with a combination of vegetation and water features, Hong and Jeon [45] provided principles for designing sound and visual components for the enhancement of urban soundscapes. Zhao et al. [46] utilized a machine learning approach to sense urban soundscapes from street view imagery and uncover the relationship between visual features and human soundscape perception. Ren et al. [47] also explored the perceived characteristics of the audiovisual environment in urban pedestrian streets with traffic noise and their influences on the environmental health of these streets. These studies collectively contribute to a deeper understanding of how streetscapes can promote psychological restoration through multifaceted design.

2.3. Limitations in Audiovisual Perception Research Concerning Streetscape

Despite advancements, current investigations into the audiovisual perception of streetscapes still exhibit certain limitations. Firstly, the majority of research relies on cross-sectional data, which do not adequately capture the long-term dynamics of environmental changes [48]. For instance, seasonal variations—such as changes in vegetation density—can significantly alter the visual and auditory characteristics of streetscapes. These temporal changes are often overlooked in cross-sectional studies, which fail to account for how such dynamic factors influence public perception over time. Secondly, many studies focusing on environmental perception tend to analyze visual or auditory elements in isolation, thereby lacking a comprehensive examination of both aspects [49]. Thirdly, existing audiovisual research has explored associations among various environments and perceived restoration, such as urban and natural parks, urban squares, and commercial streets [50]. Nonetheless, there is an absence of studies that provide a thorough evaluation of multiple street types and their interconnections.

The public's audiovisual perceptions of different types of urban streetscapes are an integral part of reaching Sustainable Development Goal (SDG) 11—Building sustainable cities and communities. Streets exhibit a wide spectrum of types, distinguished by varying architectural designs, degrees of green space integration, and patterns of pedestrian activity. With this in mind, the present study is an attempt to conduct an assessment of the public's audiovisual perceptions, taking into account seasonal variations across diverse streetscapes, by employing time-series imagery data of streetscapes.

3. Materials and Methods

3.1. Study Area

The study area was Nanjing, Jiangsu Province, one of the first batches of urban design pilot cities approved by the Ministry of Housing and Urban-Rural Development of China (Figure 1). According to the *Nanjing Street Design Guidelines* [18], streets are classified into four types based on the functional relationship of land and buildings along the route. These include traffic, living, comprehensive, and service streets. As shown in Figure 2 and Table 1, the streets selected as case studies are specifically highlighted in the guidelines, confirming that they represent the different street types found in Nanjing.

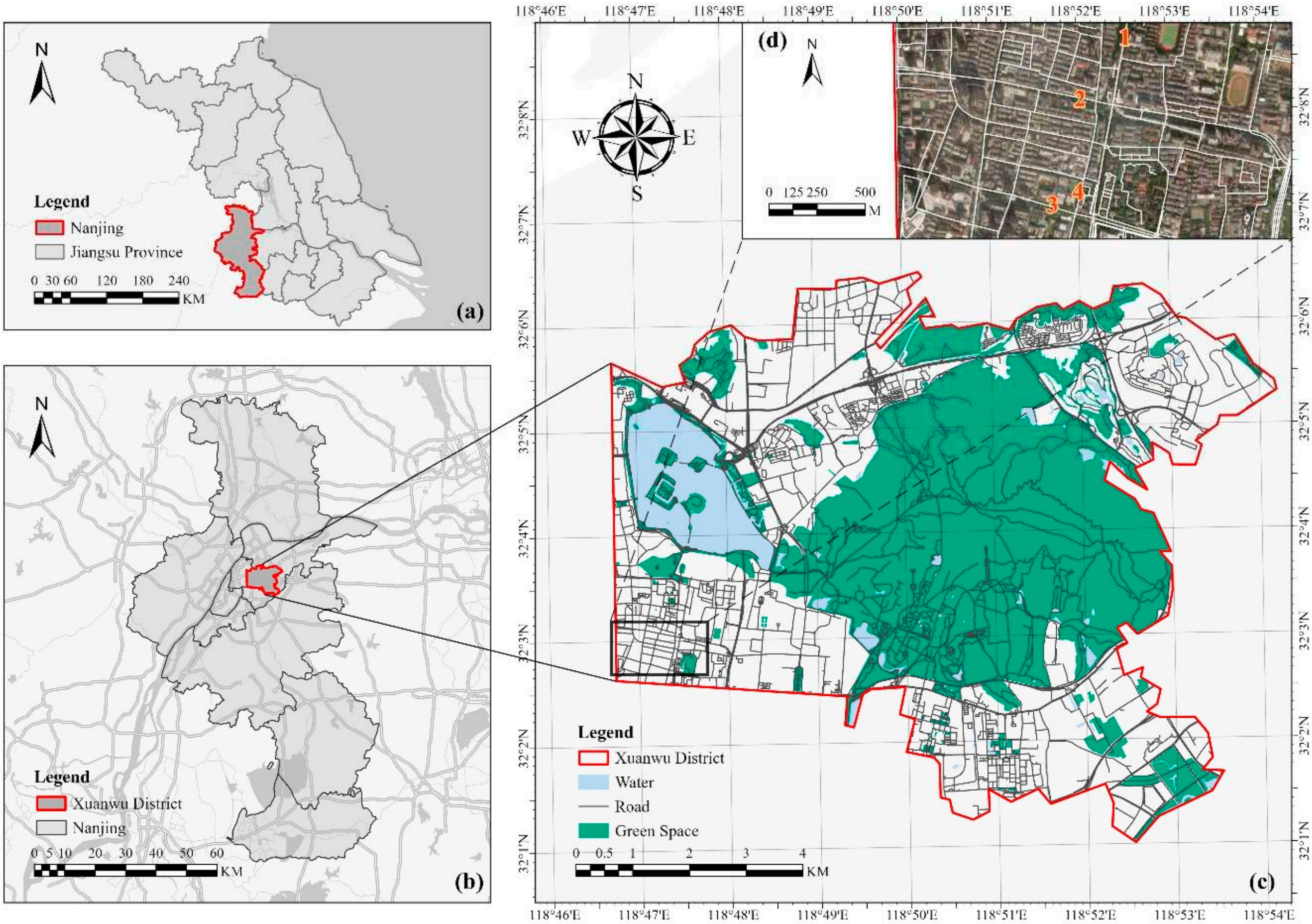

Figure 1. Location of the streets selected as case studies. (**a**) Jiangsu Province, (**b**) Nanjing City, (**c**) Xuanwu District, (**d**) Distribution of selected streets: (1) Taiping North Road, (2) Zhujiang Road, (3) Changjiang Road, (4) Beiting Lane.

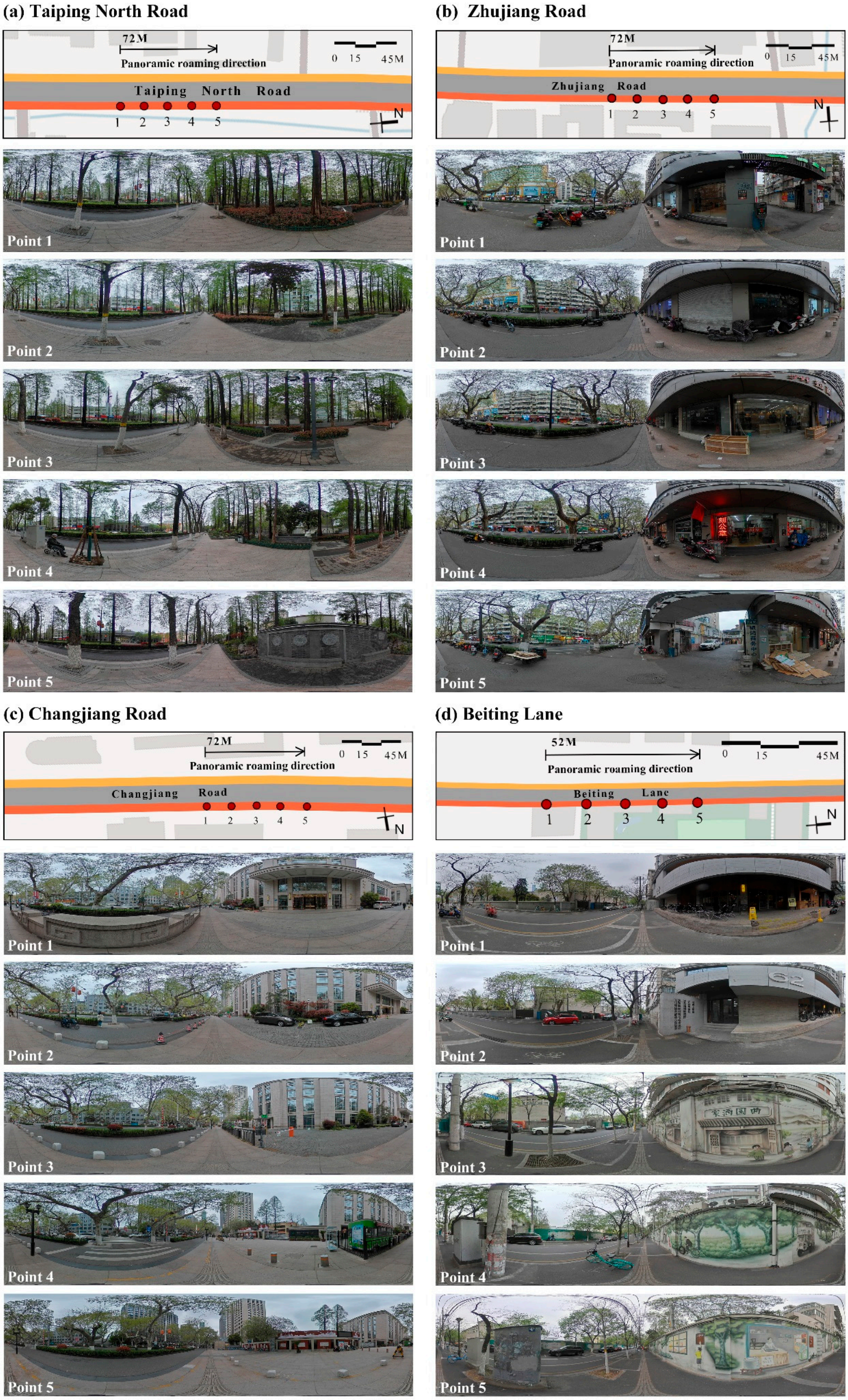

Figure 2. Images of the streets selected as case studies. (**a**) Taiping North Road, (**b**) Zhujiang Road, (**c**) Changjiang Road, (**d**) Beiting Lane.

Table 1. Street types as classified in the Nanjing Street Design Guidelines.

Street Functional Type	Description	Typical Street
Traffic street	Streets with a predominantly non-open interface along the street, with a predominantly pass-through traffic and a strong transit-oriented function.	Taiping North Road
Living street	Streets along which commercial facilities, cultural facilities and public service facilities predominate, and where the public life and activities of citizens are more concentrated.	Zhujiang Road
Comprehensive street	Streets with a mix of functional attributes and interface types of parcels and buildings along the street, with a mix of traffic and amenities.	Changjiang Road
Service street	Streets along which there is a predominantly non-open interface and which are primarily used to address logistical motorized traffic and collectors.	Beiting Lane

3.2. Stimulus

3.2.1. Visual Stimuli

Panoramic street image data were collected on the selected sample streets using the RICHO THETA SC2 device (RICHO Company, Ltd., Tokyo, Japan). To maintain the continuity and authenticity of the walking experience, five sampling points were established along the selected streets, spaced at intervals ranging from 13 to 18 m, depending on the streets' length (Figure 2). According to the China Health Association [51], the average height for adult females in China is 1.58 m and for adult males, 1.697 m. Therefore, a height of 1.5 m, simulating eye-level height, was maintained by utilizing a tripod during the image capture process. To mitigate the potential impact of weather conditions on the experimental outcomes, the image capture was conducted at 11:00 a.m. on cloudy days. To effectively illustrate the time variation on the streets, we captured photographs two months apart during spring, specifically on 5 March 2024, and 2 May 2024, from identical locations along each street.

To reduce the impact of lighting variations and the presence of pedestrians during the collection periods, Photoshop CC 2019 was employed to standardize the lighting conditions of the sample images for each street at each designated point. This adjustment ensured that the panoramic images maintained a clear forward field of view, free from close pedestrian disruptions. Given the limited social spaces on streets, we focused on visual exposure scenarios corresponding to necessary/optional walking activities based on Gehl's activity classification theory [30].

This study focuses on the green view index (GVI) as the core visual metric, given its established role as one of the strongest visual predictors of walking satisfaction [52]. While streetscape quality involves multidimensional factors such as safety (e.g., traffic control) and livability (e.g., seating facilities), previous evidence shows that natural elements like trees and grass demonstrate the strongest correlation with visual preference compared to cultural facilities or water bodies [11,53]. This supports our research approach of revealing vegetation dynamics through dual-temporal GVI comparisons.

Following this, PSPNet was employed to assess variations in the GVI of the streetscape. By leveraging the ADE20K dataset, we classified pixel points within the panoramic images, identifying various landscape components such as the sky, buildings, sidewalks, trees, and grass, assigning category a distinct color (Figure 3). This allows for the calculation of proportional changes in different elements within images captured at the same street location on two separate occasions, thereby serving as a reference for alterations in the GVI (Table 2).

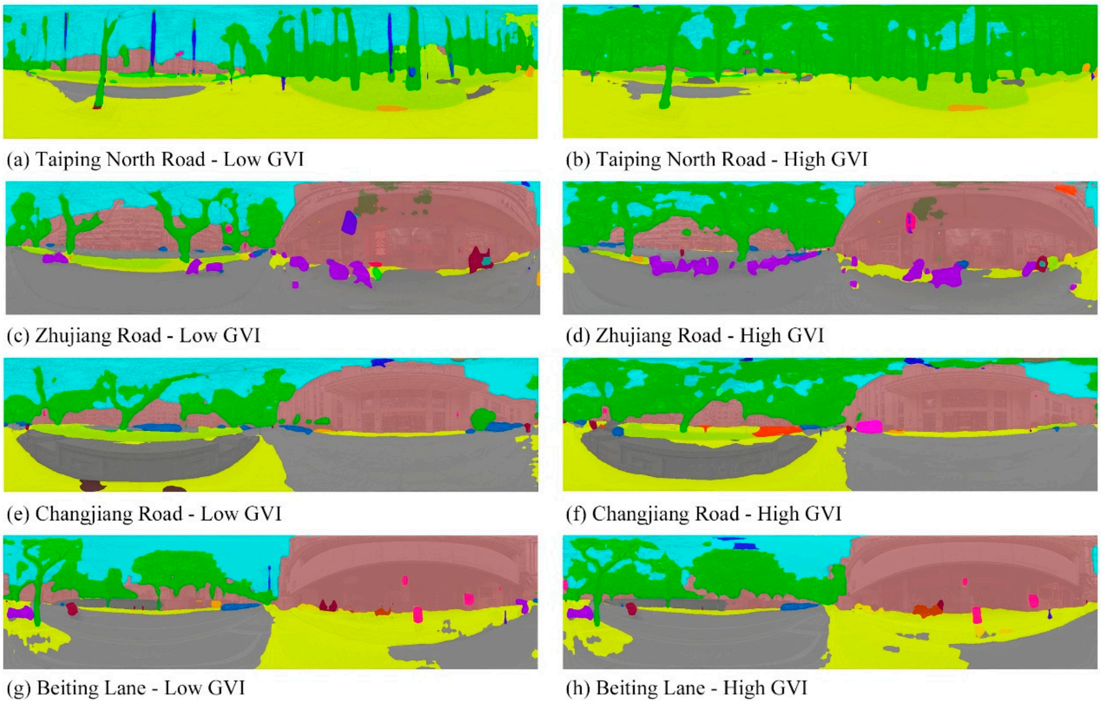

Figure 3. Examples of streetscape image semantic segmentation (one sample point per street). Color code: sky (blue), tree (green), grass (bright green), road (grey), pavement (yellow), building (brown), wall (dark grey), motorcycle (purple).

Table 2. Street GVI statistics.

Street Name	Time	GVI/% Point 1	Point 2	Point 3	Point 4	Point 5	Average/%	Variation/%
Taiping North Road	First Capture	28.96	29.41	27.17	25.81	18.70	26.01	+19.28
	Second Capture	55.54	47.61	41.54	44.66	37.09	45.29	
Zhujiang Road	First Capture	7.35	11.58	7.56	9.68	7.42	8.72	+9.85
	Second Capture	19.26	19.47	16.34	18.14	19.64	18.57	
Changjiang Road	First Capture	13.97	18.72	19.88	17.13	22.70	18.48	+8.83
	Second Capture	23.17	28.31	26.75	30.00	28.33	27.31	
Beiting Lane	First Capture	10.51	8.50	7.70	17.48	10.85	11.01	+10.72
	Second Capture	14.54	17.86	15.57	35.89	24.78	21.73	

3.2.2. Auditory Stimuli

A three-minute audio recording of street sounds was captured using a Zoom H3-VR recorder at locations representative of the typical acoustic characteristics of each street (refer to Table 3). Concurrently, during the collection of image and sound data for the experiments, sound levels were assessed and recorded at each specified location along all experimental routes utilizing a smartphone application that features a dB Meter. The primary sound levels recorded at each point (Figure 2), along with the average sound levels for each street, are presented in Table 3.

The street sounds collected were processed using Adobe Audition CC (2021) software to create a three-minute original sound piece for each street. Furthermore, to effectively mimic an improved sound environment, birdsong was mixed and combined with the original sound. The survey was carried out in late spring, leading to the selection of resident birds over migratory species, given the colder winter conditions in Nanjing. The Daurian Redstart (*Phoenicurus auroreus*) was chosen, which is a common species in Nanjing, typically inhabiting shrubs and low trees in residential areas as well as urban fringes and forests.

Table 3. Street sound-level statistics.

Street Name	Sound Level/dB					Average/dB
	Point 1	Point 2	Point 3	Point 4	Point 5	
Taiping North Road	63	64	52	69	57	61
Zhujiang Road	69	58	70	63	71	66.2
Changjiang Road	72	70	70	71	66	69.8
Beiting Lane	59	61	55	59	69	60.6

Each added sound clip was measured and calculated by the Decibel Addition Formula in accordance with GB/T 3222.1-2022: Acoustics—Description, Measurement and Assessment of Environmental Noise—Part 1: Basic Quantities and Assessment Procedures [54]. The process involves taking each individual decibel level, reverting it to its original linear scale, aggregating these values, and subsequently converting the total back into a decibel level. After the birdsong was added to each targeted sample, the total decibels were increased by merely 1~2 dB, which is below the realm of human-perceived changes in sound level. In total, eight three-minute audio segments were produced, each street corresponding to one segment of original street audio and one segment featuring the edited street audio combined with the birdsong.

3.2.3. Panoramic Roaming Scene

The 720yun platform (https://www.720yun.com/, accessed on 5 May 2024) was used to develop VR panoramic roaming scenes, with links to various scenes available in Table S1 in Supplementary Materials. Users can interact with the environment at each location by dragging the screen onto the webpage and can navigate to additional points by clicking the arrow icon, akin to the Google Street View experience. As mentioned in Sections 3.2.1 and 3.2.2, panoramic images from five locations on each street were uploaded to the 720yun platform, categorized by different street types and GVI levels. Meanwhile, the original street audio and a mixed audio track featuring birdsong (hereafter referred to as birdsong audio) were incorporated where applicable. Consequently, four distinct roaming scenes were created for each street type: control group (original sound with low GVI), sound group (birdsong with low GVI), vision group (original sound with high GVI), and combination group (birdsong with high GVI) (Figure 4).

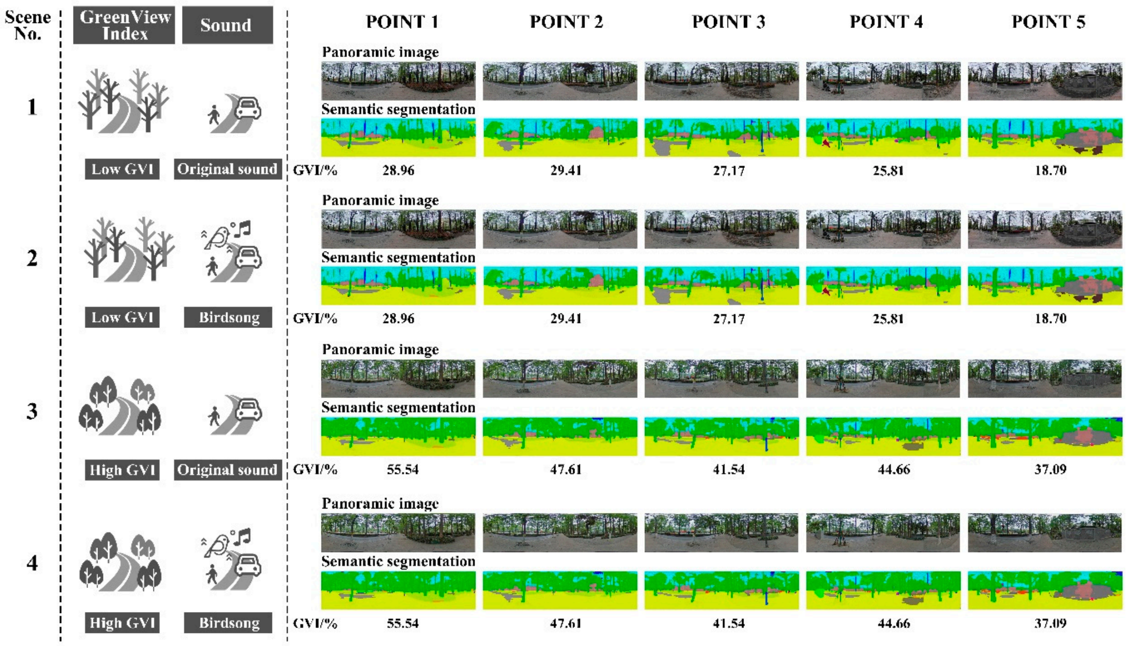

Figure 4. Illustration of experiment design (using Taiping North Street as an example).

3.3. Measurements

3.3.1. Overview

An online survey using a randomized scenario experimental design methodology was conducted through the open platform, Credamo (https://www.credamo.com/, accessed on 10 May 2024). This platform boasts an online sample base exceeding 3 million participants and has demonstrated effectiveness in previous research [55], which can therefore ensure data validity and sample recruitment. The questionnaire consisted of three parts. The first section gathered demographic details about the participants, including gender, age, occupation, education level, residential environment, and psychological health status. The second and third sections involved one control group and one of the three experimental groups (sound group, vision group, or combination group) with related questions. These questions included visual comfort assessment, acoustic environment assessment, and ratings based on the revised PRS.

3.3.2. Psychological Health Status

To understand the pre-test psychological health status of the participants, two entries in the K6 scale (Kessler 6 Psychological Distress Scale, K6) were selected [56]. Participants were asked to rate two psychological conditions, "upset or irritable" and "depressed to the point of not being able to feel happy in any way", based on their psychological condition in the past month, with responses including "don't feel that way", "some of the time", "more of the time", "most of the time", and "all of the time". Each of the five responses received a score ranging from 1 to 5 points, where higher scores for two entries suggested the presence of more severe psychological issues.

3.3.3. Visual Comfort Assessment

In light of the varying characteristics of typical landscape elements across different street types, distinct assessment criteria for visual comfort were employed. Specifically, all participants evaluated the visual comfort of "green space" and "sidewalk" within the four scenes. Furthermore, participants assigned to specific street types evaluated relevant visual elements, including "vignette facilities (seating benches, scenic walls, etc.)" on Taiping North Road, "stores along the street" on Zhujiang Road, "auxiliary facilities (guardrails, road stakes, etc.)" on Changjiang Road, and "vignette facilities (scenic walls, etc.)" on Beiting Lane. Each item was evaluated using a five-point Likert scale ranging from "1 = very uncomfortable" to "5 = very comfortable".

3.3.4. Acoustic Environment Assessment

Pleasantness, quietness, and appropriateness were selected as the indicators for acoustic environment assessment [57,58]. Pleasantness and quietness pertain to the subjective feelings of enjoyment or tranquility experienced by individuals in relation to the acoustic surroundings, while appropriateness reflects the extent to which the acoustic environment aligns with the visual environment. Building on Osgood [59], the acoustic environment was evaluated using a semantic differentiation scale ranging from 1 to 5, comprising "unpleasant-pleasant", "unquiet-quiet", and "unsuitable for the visual environment-compatible with the visual environment", according to their perception of the acoustic environment.

3.3.5. Perceived Restorativeness Scale (PRS)

The Perceived Restorativeness Scale (PRS), based on the Attention Restoration Theory, was developed and validated by Hartig [22] and has been widely utilized in the evaluation of restorative benefits in the physical environment. In the field of soundscape restoration, a Perceived Restorativeness Soundscape Scale (PRSS) was developed and tested to assess perceptions of a soundscape's potential to provide psychological restoration [29]. Building on PRS and PRSS, we developed a revised version of PRS that considered both visual and auditory environments, containing three statement items in each dimension: fascination, being away, compatibility, and extent (Table 4).

Table 4. The revised Perceived Restorativeness Scale.

Dimensions	PRS Statement
Fascination (F)	F1-I find this visual and sound environment appealing. F2-There is so much to explore and discover here. F3-I would like to spend more time looking at my surroundings.
Being away (B)	B1-The visual and auditory environment here helps me to relax my mind. B2-The visual and auditory environment here makes me feel free from the stress of daily work for a while. B3-The visual and auditory environment here lets me take a break from my daily routine and responsibilities.
Compatibility (C)	C1-The visual and auditory environment fits with my personal preferences. C2-I can do the things I like to do here. C3-I rapidly get used to seeing the visual environment and hearing this type of auditory environment.
Extent (E)	E1-The sounds I am hearing seem to fit together quite naturally with this place I see. E2-It's a place that allows me to fit in without feeling constrained. E3-It's a place that inspires a lot of good thoughts in me.

3.4. Experimental Design

Each participant was randomly assigned to one control group and one of the three experimental groups (Table 5). To eliminate potential order bias, the order in which participants viewed the two scenes was randomized via the Credamo platform. Participants were asked to take part in the experiment only on the computer side and in a tranquil setting to enhance the overall roaming experience. The experimental procedure and time required for each phase are shown in Figure 5.

Table 5. Street sample groupings.

Street Name (Function)	Test Group	Group Name	GVI	Sound Type
Taiping North Road (Traffic street)	1	Control	Low	Original sound
		Sound	Low	Birdsong
	2	Control	Low	Original sound
		Vision	High	Original sound
	3	Control	Low	Original sound
		Combination	High	Birdsong
Zhujiang Road (Living street)	4	Control	Low	Original sound
		Sound	Low	Birdsong
	5	Control	Low	Original sound
		Vision	High	Original sound
	6	Control	Low	Original sound
		Combination	High	Birdsong
Changjiang Road (Comprehensive Street)	7	Control	Low	Original sound
		Sound	Low	Birdsong
	8	Control	Low	Original sound
		Vision	High	Original sound
	9	Control	Low	Original sound
		Combination	High	Birdsong
Beiting Lane (Service street)	10	Control	Low	Original sound
		Sound	Low	Birdsong
	11	Control	Low	Original sound
		Vision	High	Original sound
	12	Control	Low	Original sound
		Combination	High	Birdsong

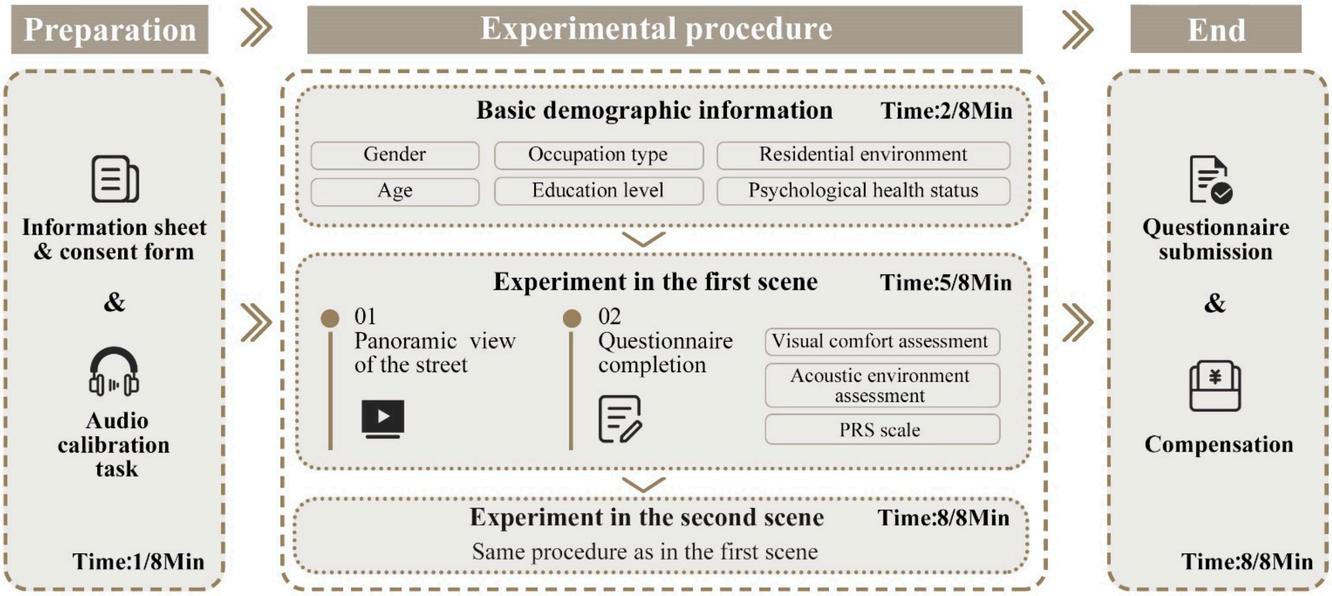

Figure 5. Experimental procedure. Note: The arrows show the direction of progression.

Prior to starting the experiment, the participants were briefly introduced to the research aims and process. They were asked to do an audio calibration task to make sure the experimental samples played the sounds correctly and to improve the consistency of the sound presentation among different people. Then, they were asked to fill in the socio-demographic information and pre-test psychological health status. The participants were then directed to click on a web link to access the first panoramic street walkway, where they were encouraged to visualize themselves within the depicted environment and to immerse themselves in the experience for a minimum of two minutes. Then, they were asked to complete the visual comfort assessment, the acoustic environment assessment, and the PRS. Following the same procedure, participants were asked to view the second scene and complete the questionnaires. Finally, they were allowed to leave the experiment.

3.5. Statistical Analysis

The collected questionnaires were screened to exclude questionnaires with lower response quality such as repeated responses using the same IP address, choosing the same option for multiple consecutive questions, and short response time (i.e., <200 s). Prior to conducting data analysis, the reliability and validity of the questionnaire scales were assessed utilizing Cronbach's alpha via SPSS 26.0. Using Amos 28.0 software, a confirmative factor analysis was conducted to determine the factor structure of the PRS questionnaire. Factor loadings at each item should be greater than 0.40 and should average at least 0.70 at each construct.

The visual comfort assessment, acoustic environment assessment, and the Perceived Restorativeness Scale (PRS) were examined using the mean value of participants' ratings.

Independent two-sample *t*-tests were conducted to assess the differences between the sound group and the control group, as well as between the vision group and the control group, in response to Research Question I. In addition, a one-way ANOVA was performed to investigate the main effects of vision and sound, as well as their interaction effect, on restorative outcomes (Research Question II). If significant effects were identified in the ANOVA, post hoc tests using Bonferroni correction were conducted to examine specific group differences [60]. The significance level was set at 0.05. To assess whether participants' perceptions varied across different groups, we analyzed and reported the mean differences (ΔM) between the experimental groups:

$$\Delta M = \text{Mean}(\text{Experiment group 1}) - \text{Mean}(\text{Experiment group 2})$$

4. Results

4.1. Participants Information

Out of 360 participants, a total of 360 valid questionnaires were collected. Each group comprised 30 participants, satisfying the minimum sample size required for statistical analysis [61]. Participants' demographic information is listed in Table 6. Among the respondents, 140 were male, representing 38.9%, while 220 were female, accounting for 61.1%. The majority of participants fell within the age range of 18 to 40 years, and most had attained a high school education. Additionally, a significant portion of the participants resided in urban areas, comprising 93.9%, indicating a notable level of familiarity with urban streetscape environments.

Table 6. Overall fit coefficient of PRS.

Category		Number	Percentage/%	Cumulated Percentage/%
Gender	Male	140	38.9	38.9
	Female	220	61.1	100.0
Age	18–30	189	52.5	52.5
	31–40	135	37.5	90.0
	41–50	17	4.7	94.7
	51–60	16	4.4	99.2
	Above 60	3	0.8	100.0
Education level	Junior school degree or equivalent	1	0.3	0.3
	High school degree or equivalent	13	3.9	3.9
	Bachelor's degree or equivalent	284	78.9	82.8
	Master's degree and above	62	17.2	100.0
Occupation	Student	87	24.2	24.2
	State-owned enterprises	38	10.6	34.7
	Public institution	42	11.7	46.4
	Civil servant	18	5.0	51.4
	Private enterprise	141	39.2	90.6
	Foreign company	24	6.7	97.2
	Freelancer	8	2.2	99.4
	Other	2	0.6	100.0
Living environments	Urban environments	338	93.9	93.9
	Rural environments	22	6.1	100.0

The validity of participants' answers was first examined. Cronbach's value for PRS was 0.968. Cronbach's α metrics for visual comfort of the four streets were 0.655, 0.842, 0.823, and 0.715; for the sound environment assessment, Cronbach's α = 0.842. Using Amos 28.0 software, confirmative factor analysis was conducted on the PRS questionnaire. The factor loading value for fascination, being away, compatibility, and extent dimensions were all above 0.7, which indicates the convergence validity was ideal, and the construct validity and convergence validity of the PRS used in this experiment reached the standard.

4.2. Research Question I: Can Vision and Sound Independently Enhance Restoration When Considering Different Street Types?

Among the four distinct streetscapes, both vision and sound groups exhibited enhancements in specific aspects of the restorative effects of these environments when compared to the control group (see Tables S2–S5 in Supplementary Materials).

For Taiping North Road, categorized as a traffic road, the sound group demonstrated a significant improvement in the greenness of visual comfort assessment (p = 0.023), acoustic environment assessment ($p < 0.001$, in all dimensions), and the PRS ($p < 0.001$, in all dimensions). Conversely, the vision group did not show significant changes in these three measurements.

For Zhujiang Road (living street), participants in the sound group reported significant increases in the pleasantness and quietness aspects of the acoustic environment assessment ($p < 0.001$), along with enhancements in the four dimensions of PRS ($p = 0.001$, $p < 0.001$, $p = 0.002$, and $p = 0.011$). In contrast, the vision group only exhibited significant differences in the visual comfort assessment related to green space ($p = 0.005$).

For Changjiang Road (comprehensive street), the sound group displayed significant differences from the control group, excelling in acoustic environment assessment ($p < 0.001$) and the PRS ($p < 0.001$). Additionally, it surpassed the control group in the dimensions of green space ($p = 0.006$) and street furniture ($p = 0.017$) within the visual comfort assessment. However, the vision group did not show any significant differences from the control group.

Finally, for Beiting Lane (service street), the sound group outperformed the control group in all aspects of visual comfort assessment, acoustic environment assessment, and PRS. In addition, the vision group indicated that enhancing the greenness of the streetscape could significantly improve the greenspace dimension of visual comfort assessment ($p = 0.048$), the quietness aspect of acoustic environment assessment ($p = 0.024$), and all dimensions of PRS ($p = 0.036$, 0.013, 0.020, 0.038, respectively).

4.3. Research Question II: Can the Combination of Vision and Sound Enhance Restorative Effects Compared to Their Independent Roles, When Considering Different Street Types?

The analysis presented in Table S6 of Supplementary Materials indicates that notable disparities exist among the four street groups regarding the greenness of visual environments, the pleasantness, quietness, and happiness associated with acoustic environment assessments and the PRS. Significant differences were observed between the sound group and the vision group, as well as between the vision group and the combination group. Conversely, no significant differences were identified between the sound group and the combination group.

For Taiping North Road, the sound group exhibited a notable increase in pleasantness ($p = 0.002$), quietness ($p = 0.01$), and appropriateness $p = 0.01$) when compared to the vision group in their assessment of the acoustic environment. Additionally, the sound group significantly outperformed the vision group in the PRS regarding attractiveness ($\Delta M = 3.83$, $p < 0.001$), being away ($\Delta M = 3.93$, $p < 0.001$), compatibility ($\Delta M = 3.90$, $p < 0.001$), and extent ($\Delta M = 4.47$, $p < 0.001$). Conversely, the combination group demonstrated a significant improvement in perceived restorativeness relative to the vision group, particularly in the greenness of visual environments ($\Delta M = 0.53$, $p = 0.02$), pleasantness ($\Delta M = 1.00$, $p = 0.02$), quietness ($\Delta M = 1.13$, $p = 0.01$), and appropriateness ($\Delta M = 1.13$, $p = 0.02$) of the acoustic environment. Furthermore, significant differences were also identified on the PRS between the vision group and combination group. However, no significant differences were observed between the sound group and combination group.

A comparable trend was noted for Zhujiang Road. In terms of alterations in green space, the combination group exhibited a significantly greater impact than the sound group ($\Delta M = 0.57$, $p = 0.04$). When assessing the acoustic environment, the sound group demonstrated a notable advantage over the vision group, with an estimated difference of 1.07 ($p = 0.004$) for the dimensions of pleasantness and quietness, and 0.93 ($p = 0.043$) for quietness. Additionally, significant disparities were identified between the combination group and the vision group, with differences of 1.40 ($p = 0.000$) and 1.37 ($p = 0.001$) in the pleasantness and quietness dimensions, respectively. Regarding the PRS evaluation, the sound group surpassed the vision group in fascination and extent dimensions, while the combination group excelled over the vision group across all four dimensions of PRS.

For Changjiang Road, no significant differences were observed in the visual comfort assessment. However, notable differences emerged in the acoustic environment assessment and PRS. Specifically, the sound group significantly outperformed the vision group in the pleasantness and quietness dimensions, with *p*-values of <0.001, 0.007, and 0.021, respectively. In the PRS evaluation, the sound group also excelled over the vision group in fascination, being away, compatibility, and extent. Similarly, significant differences were noted between the combination group and the vision group, with the combination group outperforming the vision group in all aspects of the acoustic environment assessment and PRS. Nonetheless, no significant differences were found between the sound group and combination group.

For Beiting Lane, significant increasements were observed in the acoustic environment assessment in the sound group compared to the vision group as well as between the combination group and vision group. However, these metrics were not evident in the vision comfort assessment between the three groups. In terms of PRS evaluation, the sound group significantly outperformed the vision group in the pleasantness, fascination, compatibility, and extent dimensions, with *p*-values of 0.004, <0.001, 0.016, and 0.023, respectively. The combination group also significantly outperformed the vision group in all dimensions of the PRS evaluation. However, the difference between the combination group and sound group was not significant.

5. Discussion

5.1. The Independent Role of Vision and Sound

In this study, three dimensions of restorativeness evaluation were applied, including visual comfort assessment, acoustic environment assessment, and PRS. It is worth noting that both soundscape interventions alone and combined audiovisual interventions resulted in similar significant enhancements across three aspects of evaluations among the four streets. On the other hand, the visual interventions (enhanced GVI) had a limited effect on acoustic environment assessment and PRS evaluation. In other words, it seems that in the street-setting experiments, visual interventions (enhanced GVI) cannot independently exhibit a significant improvement on environmental perceptions, while audio intervention can.

In previous studies, it was believed that audio and visual perceptions are connected, where visual and audio factors tend to influence each other rather than in one direction [62]. It was confirmed that, in urban squares and parks, the relative visual elements, such as openness, greenspace, and spatial patterns, have key impacts on the acoustic comfort level, and adding natural sound sources such as water sounds and birdsong can lead to the enhancement of the visual comfort level [63–65]. However, street space is different from other open spaces, as users of street space mainly pass through it rather than stay in it for a long time. Perhaps because of this characteristic, changing the GVI had a limited effect on the overall environmental comfort.

Compared to the impact of visual intervention, in this study, the enhancement of auditory stimuli had a more significant positive effect on visual comfort. Similar findings have also been found in previous studies, indicating that most people's environmental perceptions are dominated by audio elements [66]. The reasons for this phenomenon may be explained by two points. On the one hand, traffic noise was found to be the most significant factor affecting environmental perception, so the birdsong added in this experiment may have had a masking effect on the traffic sounds, thus creating a more significant enhancement in environmental perception [42]. Other possible explanations could be attributed to the manner in which visual stimuli are reproduced. Despite significant advancements in digital technology that have improved the immersive quality of digital research samples, accurately replicating the intricacies of real-world scenes continues to pose a challenge. Perhaps in digital research samples, changes in visual elements do not capture subjects' attention as much as audio elements do, causing visual elements to have an insignificant impact.

5.2. Audiovisual Interactions in Different Types of Streets

This study also highlighted the differences in environmental intervention effects due to varied street types, exploring four function types of streets—traffic, living, comprehensive, and service streets—according to *Nanjing Street Design Guidelines* [18]. These street types exhibit distinct functional purposes, which influence the types of activities they support, as categorized by Gehl: necessary, optional, and social activities [30].

For example, Taiping North Road exemplifies integrated urban design, where there is the coexistence of green infrastructure and public facilitates, both necessary and optional activities. In contrast, Zhujiang Road, a commercial-residential hybrid area, primarily supports necessary activities like grocery shopping and commuting, with occasional optional activities such as informal conversations or leisurely strolls. Changjiang Road, adjacent to government offices, is dominated by necessary activities related to official business, with its formal setting limiting opportunities for optional or social interactions. Beiting Lane, however, stands out with its narrow width and wall murals, creating an environment conducive to optional and social activities.

The initial green view index (GVI) of the four streets further highlights their differences (Table 2). Taiping North Street ranked the highest, with an average GVI of 25.96%, followed by Changjiang Road with 18.48%. Previous studies indicated that when the GVI reached around 25%, the effect from greenery started to level off [67,68]. In other words, the lack of improvement effect on these two streets after the increase in GVI was perhaps due to the fact that their initial GVI had already reached a considerably high level. In contrast, the improvement effect from green visibility was only seen in Beiting Lane, where both audio and audiovisual interventions have shown significant impacts on Beiting Lane compared to the other streets. This can be attributed to its unique characteristics, such as existence of murals (refer to Table S1 in the Supplementary Materials) and a height-to-width ratio nearing 1 [44,69], which may have enhanced the effectiveness of visual and sound interventions. These features align with Gehl's concept of optional and social activities [30], where aesthetic and environmental qualities play a crucial role in encouraging user engagement.

Statistical analysis (e.g., ANOVA) revealed that the impact of auditory, visual, and audiovisual elements did not significantly differ across street types. However, the sound group and the combination group outperformed the vision group, while no significant difference was observed between the sound group and the combination group. These findings underscore the importance of prioritizing soundscape design in urban planning to enhance environmental quality and user experience, particularly in streets where optional and social activities are encouraged.

5.3. Theoretical and Practical Contributions

Prior studies have predominantly examined the visual or auditory aspects of perceived restorativeness in isolation. Our research introduces a multi-sensory framework that integrates time-series street view images (e.g., extracting GVI) with on-site acoustic recordings (e.g., measuring sound pressure levels and implementing natural sound sources). Using a randomized controlled experiment with a control group and three sensory-adjusted groups, we examined the independent and interactive effects of vision and sound on the perceived restorativeness of streetscapes, considering street type variations. This contribution introduces a novel multi-sensory perspective to the existing research on restorative landscape.

This research also provides implications for planning practices. In this study, audio intervention has a more significant impact on the overall environmental perception, compared to visual intervention. This suggests that future street design and regeneration should consider enhancing environmental quality from the perspective of soundscape design. The concept of soundscape intervention aims to improve the composition of sound sources and sound perceptions by employing spatial, landscape, and environmental design at various scales. There are two primary approaches to soundscape intervention design: the introduction of positive sound sources or the masking of noise [70,71]. The results of this study support a dual strategy for soundscape optimization in future urban street design and regeneration:

Macro-scale and long-term strategy—ecological soundscape development: This involves systematically enhancing the street's bio-acoustic potential through biodiversity-focused plant and waterscape design (e.g., increasing avian soundscape richness by adding broadleaf canopy coverage; implementing cascading water features that produce broadband masking effects across the 200–5000 Hz range), thereby establishing spatiotemporally continuous natural sound matrices [36,72].

Micro-scale and short-term strategy—psychoacoustic intervention: Since traffic noise poses the primary threat to street soundscapes, its impact can be mitigated by combining positive sound masking (e.g., deploying speakers that release white noise, integrated into smart lighting systems to mask traffic noise based on its patterns) with cognitive diversion techniques (e.g., embedding music or culturally significant auditory cues to shift attention) [73]. The guidelines for enhancing street soundscapes are context specific. For instance, in living streets, where tranquility and community are prioritized, the incorporation of bird calls or rustling leaves can add a calming sense. On comprehensive streets, where a variety of activities occur, the use of water features combined with soft background music or auditory cues that resonate with the local culture can create a more pleasant auditory environment.

On the visual side, the effectiveness of enhancing GVI in different streets depends on the streets' initial conditions and types. These results support policies such as integrating thresholds in GVI. For streets with low initial GVI, planners should prioritize integrating green resources to maximizing the restorativeness effect, e.g., by cultivating plants with expansive canopies in limited spaces and integrating vertical greenery systems, to enhance the green view ratio from perceptual aspect, thereby maximizing the restorative benefits of green landscapes. For streets with already high GVI, the impact of further increasing greenness is limited. Therefore, planners should consider the influence of other factors such as spatial parameters, plant species diversity, color schemes, and layout to achieve further improvements in visual appeal and functionality. While this study offers valuable insights for urban design practice, it captures only a portion of the complex factors shaping streetscape perception. Effective landscape design must integrate diverse considerations—from environmental characteristics and human spatial behavior to ecological sustainability and cultural significance—to achieve truly livable, high-quality urban spaces.

6. Conclusions

Streets occupy a high percentage of urban public space and play a vital role in restorativeness. Prior research has primarily examined the independent effects of vision on perceived restorativeness, with few research endeavors into the independent and interactive effects of sound and vision on the public perception of restorativeness. Using a randomized controlled experiment with a control group and three sensory-adjusted groups, we looked into the effect of four different types of streets: living, traffic, comprehensive, and service streets. It was found that interaction effects of vision and sound contributed to enhanced perceived restorativeness. Sound contributed to better restorative effects compared to vision, while the differences between the sound and combination groups were not significant. The research findings highlight introducing positive sound sources or enhancing the masking effect of soundscape in street environmental design.

This study has limitations in terms of the following aspects: Firstly, the limited sample size and control over variables prevented the inclusion of additional visual and auditory variables across various groups. Future research should expand the scope by integrating a wider range of interrelated variables—such as street spatial morphology, visual exposure diversity, and sound pressure levels—to more comprehensively assess the complexity of streetscape perception. Secondly, the experiments were conducted through online recruitment, which introduces the potential for participants to experience slight differences in screen resolution, which could impact the findings. Future research could address these limitations and might consider the use of wearable technology and ergonomic assessments to more precisely measure participants' responses to diverse stimuli. Thirdly, our participant pool (predominantly 18–40 years) may limit generalizability due to age-related differences in mobility and perception. The online format could further exacerbate this through digital divide effects. Future studies should employ age-stratified sampling with adaptive methods (e.g., voice-assisted surveys) to better capture perspectives of the elderly.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land14040757/s1: Table S1: Links to street panoramic roaming scenes; Table S2: Taiping North Road statistical analysis; Table S3: Zhujiang Road statistical analysis; Table S4: Changjiang Road statistical analysis; Table S5: Beiting Lane statistical analysis; Table S6: Post hoc analysis of different restorativeness measurements between sound, vision, and combination groups.

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