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# An Interpretable Machine Learning Approach to Studying Environmental Safety Perception Among Elderly Residents in Pocket Parks

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**Abstract**

This research explores the environmental safety challenges faced by pocket parks in the context of urban aging within Chinese cities. It systematically analyzes visual elements that influence the elderly's perception of environmental safety by applying interpretable machine learning techniques. By integrating panoramic image semantic segmentation and explainable AI models (e.g., SHAP and PDP), the study transforms subjective environmental perception into measurable indicators and constructs an environmental safety perception model using the LightGBM algorithm. Results indicate that sufficient pedestrian areas and moderate crowd activities significantly enhance safety perception among the elderly. Conversely, the presence of cars emerges as the most substantial adverse factor. Natural elements, such as vegetation and grass, exhibit nonlinear effects on safety perception, with an optimal threshold range identified. The research further elucidates the intricate synergies and constraints among visual elements, underscoring that the highest perceived safety arises from the synergistic combination of positive factors. This study deepens the understanding of environmental perception among the elderly and offers a data-driven framework and practical guidelines for urban planners and designers. It holds significant theoretical and practical implications for advancing the refined and human-centered renewal of urban public spaces.

**Keywords:** urban aging; pocket parks; environmental safety perception; visual elements; machine learning



Academic Editor: Yung Yau

Received: 28 August 2025
Revised: 14 September 2025
Accepted: 19 September 2025
Published: 20 September 2025

**Citation:** Wu, S.; Wu, S.; Chen, J.; Pan, C. An Interpretable Machine Learning Approach to Studying Environmental Safety Perception Among Elderly Residents in Pocket Parks. *Buildings* **2025**, *15*, 3411. https://doi.org/10.3390/buildings15183411



## 1. Introduction

As the most populous country in the world, China faces an increasingly aging population. While the World Health Organization defines senior citizens as citizens aged 65 and above, the Law of the People's Republic of China on the Protection of the Rights and Interests of the Elderly defines senior citizens as those aged 60 and above. Despite recent continuous economic growth and rapid urban renewal, the built environment of many urban public spaces still fails to meet the basic needs of the elderly. With declining physical and mental health, the elderly require a more supportive living environment to enhance their quality of life [1]. Urban public spaces, particularly parks, serve as key locations for the elderly to engage in outdoor activities and interact socially within urban environments. However, these spaces often struggle to meet the needs of elderly users, not only compromising their ability to engage effectively but also exposing them to safety risks. Many urban parks exhibit facility deterioration and uneven terrain, heightening the risk of falls among older adults due to inadequate ground maintenance and facility upkeep [2]. The significant noise problem in the park adversely impacts the recreational experience of elderly individuals [3]. Research indicates that elders' perceptions of urban park safety are shaped by factors such as cleanliness and the condition of facilities [4]. Relative to large parks, pocket parks exhibit the characteristics of a small scale, flexible layout, and geographical proximity to neighborhoods. Therefore, they are more likely to function as critical venues for the daily activities of elderly residents. Pocket parks, typically smaller than one hectare, can provide functional and practical open space through thoughtful design and strategic layout [5]. As a key element of urban micro-renewal, the environmental design of pocket parks plays a essential role in enhancing the psychological well-being of the elderly population. Elderly individuals aged between 66 and 75 are frequent visitors to pocket parks, where the landscaped environment contributes significantly to psychological restoration [6]. The green coverage, spatial arrangement, and facility designs of pocket parks collectively shape both the elderly's willingness to use these spaces and their experiential quality during activities [7]. There is a gap in the current research on the quantitative analysis of pocket park environments' effects on elderly safety perception based on visual elements [8]. Prior research suggests that factors such as greening and spatial enclosure influence elderly spatial perception. However, systematic quantitative analyses on how visual elements specifically impact older adults' safety perception remain underdeveloped. Enhancing the environmental safety of pocket parks and fulfilling the functional needs of elderly individuals for secure and comfortable public spaces have emerged as critical priorities in contemporary urban renewal initiatives.

To investigate the behaviors and interactions of elderly individuals in urban public spaces, it is significant to analyze the critical role of environmental safety perception in shaping their experiences. The perception of environmental safety is a key psychological element for the elderly in urban public spaces. This perception is influenced by several theoretical frameworks, notably the Stress Reduction Theory (SRT) and the Attention Restoration Theory (ART). SRT posits that exposure to natural environments can foster positive psychological experiences, which in turn alleviates stress. Similarly, ART suggests that natural settings offer the restorative benefits necessary for individuals to recover their attentional capacity from the demands of daily stressors [9]. Safety perception exhibits significant group differences and environmental dependence. Zhou et al., through crowdsourcing research, revealed significant differences in the perception of criminal- and disability-related security between men and women, highlighting the necessity to precisely define perception and incorporate demographic variables into modeling [10]. By focusing on a female-centered perspective, Chen et al. revealed that environmental indicators such as sky openness, the visibility of greenery, and road visibility significantly influence women's sense of security [11,12]. These theories establish a decisive theoretical framework for elucidating how the elderly evaluate the safety of built environment. This study defines environmental safety perception as the elderly's subjective evaluation of their sense of security in pocket parks. This perception is shaped by two sets of factors: the physical characteristics of pocket parks (e.g., greening, spatial layout, and facility configuration) and the individual characteristics of the elderly (e.g., experience, knowledge, and emotional state) [13].

With the rapid development of computer vision and deep learning technologies, SVI and deep learning models have increasingly been employed by researchers to quantify and analyze human perception of the built environment, particularly in environmental safety perception. Larkin et al. leveraged Amazon Mechanical Turk to crowdsource annotations and trained deep models via transfer learning to predict variables such as natural environment quality, aesthetics, relaxation, and security. The model demonstrated an explanatory power of up to 77.6%. This method not only accelerates data acquisition efficiency but also enhances the objectivity and reproducibility of perceptual measurement [14]. Machine learning has been extensively applied in urban spatial data analysis, notably for evaluating how urban green spaces affect residents' mental health. However, the black-box characteristic of machine learning restricts its interpretability, thereby undermining its credibility and limiting its application to scenarios requiring explanation. Recent developments in Explainable Artificial Intelligence (XAI) offer a solution by enabling the interpretation of machine learning outcomes [15]. For instance, SHAP (SHapley Additive exPlanation) and PDP (Partial Dependency Plot) are two popular model interpretation techniques. The SHAP method, introduced by Lundberg et al. and grounded in the Shapley value from cooperative game theory, provides feature-level explanations by quantifying the contribution of each feature to the model's output for a given prediction [16]. This method enables a deeper understanding of the decision-making mechanisms in complex models, thereby enhancing their interpretability and establishing greater confidence in their predictions [17]. The SHAP method combines global and local interpretations within a unified framework. Its findings align with human perception, making it robust and intuitive for interpretation [18]. Partial dependence plots (PDP) visualize the marginal effect of individual features on the output of a machine learning model and are particularly valuable for exploring non-monotonic relationships in high-dimensional, multi-faceted data structures [19]. SHAP and PDP can be leveraged to determine the most effective intervention by quantifying feature importance and visualizing domain-specific outcomes.

Existing studies have laid a significant theoretical foundation for understanding the environmental perception of the elderly; however, several notable limitations remain. Empirical research is predominantly based on traditional questionnaires or limited field observations, thereby hindering large-scale, efficient quantitative analysis of urban public spaces. Although machine learning models have been introduced in some studies, their inherent "black box" characteristics obscure the intricate relationships underlying their prediction mechanisms. This limitation complicates the translation of research findings into practical and actionable design principles. Based on the above considerations, this study uses 29 pocket parks located on Xiamen Island, Xiamen City, Fujian Province, China as examples. Semantic segmentation technology was employed to extract visual elements from panoramic images. Subsequently, a road safety perception dataset was constructed by combining these visual elements with safety perception scores. An environmental safety perception model was established using the LightGBM algorithm. The influence mechanism of visual factors on environmental safety perception was analyzed using SHAP and PDP interpretation algorithms. The key elements and their influence intensity were analyzed.

## 2. Research Methodology

### *2.1. Research Area and Data Collection*

#### 2.1.1. Research Area

This study examines the pocket parks on Xiamen Island in Xiamen City, Fujian Province, China. During the study, 29 pocket parks (with an area of less than 1 hectare) were found to have been constructed on Xiamen Island, comprising 19 in Siming District and 10 in Huli District. As the core area of Xiamen City, Xiamen Island occupies a highly desirable geographical position between 118°04′ and 118°23′ east longitude and 24°23′ and 24°55′ north latitude and has a total area of approximately 158 square kilometers. Xiamen Island exhibits a relatively high population density and a pronounced aging trend. Based on 2022 statistics, 18.5% of the island's population was aged 60 or above, exceeding the national average. This provides an ideal case study for analyzing the spatial needs of the elderly in urban public spaces [20].

The 29 pocket parks examined in this study are distributed across various administrative districts on the island, such as Siming and Huli Districts. They encompass diverse urban environments, including high-density residential zones, mixed commercial areas, and older residential communities. Most of these pocket parks were constructed post-2010 as part of urban micro-renewal initiatives. They typically span an area of 200 to 500 square meters and are characterized by a high vegetation coverage rate—averaging over 65%—as well as a variety of facilities, including seating arrangements, walking paths, and fitness equipment.

Xiamen Island was chosen as a study site since it epitomizes the common issues faced by China's rapidly urbanizing coastal regions. Firstly, rapid economic growth has spurred urban renewal. Secondly, approximately 40% of the local communities are aging, and the discrepancy between the existing built environment and the elderly's needs is pronounced. Consequently, pocket parks have emerged as a vital experimental platform to enhance outdoor activity safety for the elderly. Xiamen Island's climate is mild, with an average annual temperature of 21 °C, and its annual precipitation is moderate at roughly 1200 mm. These conditions facilitate year-round outdoor activity research and ensure stable data collection (Figure 1).

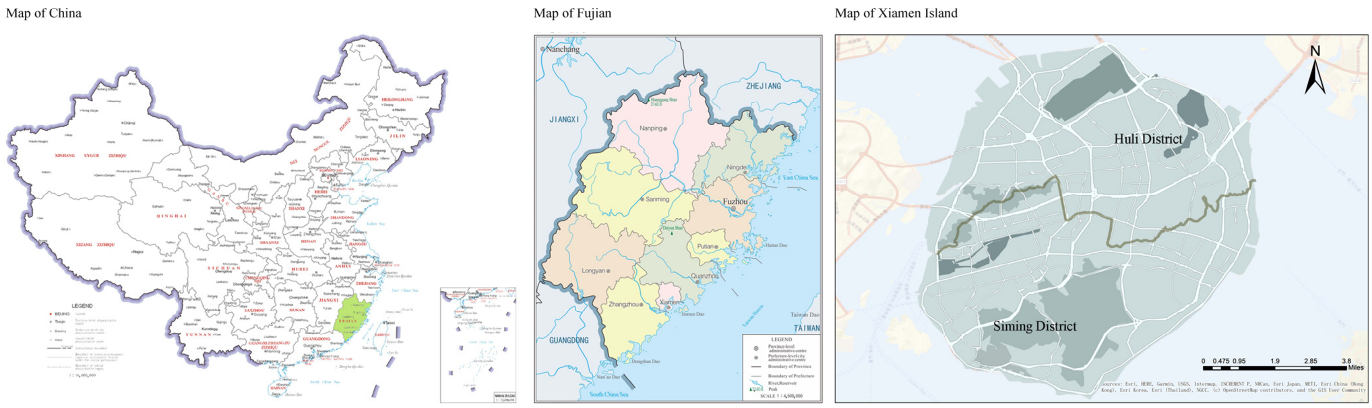



**Figure 1.** Research Scope.

### 2.1.2. Data Collection

Panoramic image data: In elderly individuals, the typical visual field spans approximately 500 m [21]. While pocket parks typically occupy areas less than one hectare with simple internal road layouts, their scenery is characterized by variety and staggered visual impact. To ensure comprehensive coverage of walking paths and scenic elements within the parks, strategic placement of collection points is essential. Collection guidelines are as follows:

1. No points are required for sections shorter than 5 m.
2. Points should be placed at the midpoint of sections ranging from 5 to 10 m.
3. For sections exceeding 10 m, points should be spaced at 20 m intervals.
4. Additionally, points should be positioned at every intersection to ensure coverage.

A total of 497 collection points and corresponding panoramic images were selected for this study. These images were captured using the Insta 360X4 panoramic camera (Shenzhen Insta360 Innovation Technology Co., Ltd., Shenzhen, China), which automatically records metadata for each photo, including geospatial coordinates, shooting time, and environmental lighting conditions. This functionality ensures data consistency and traceability. After acquisition, all 497 images underwent standardized preprocessing. Denoising and brightness normalization were applied using the OpenCV Python 3.14 library to mitigate weather-related interference (e.g., rain or harsh lighting) during visual element extraction. Images were uniformly resized to 1024 × 512 pixels to optimize input for subsequent deep learning models.

Environmental safety perception data of the elderly: This study examined the environmental safety perception of elderly individuals in pocket parks on Xiamen Island, with data collected over a 15-month period. The research team randomly selected 2000 panoramic images across multiple pocket parks and invited 88 volunteers (an equal gender distribution of 44 males and 44 females) to evaluate their environmental safety perception using a 1-to-10 semantic differential scale. The volunteers were primarily elderly residents aged 60 and above, which established the robustness and representativeness of the sample. To ensure the reliability of the scores, the research team selected volunteers with frequent use of pocket parks. Based on the 2021 Xiamen City Seventh National Population Census Report, the city's population aged 60 and above is 490,600, constituting 9.56%. The study resulted in 176,000 valid scoring data points, derived from 88 volunteers independently evaluating 2000 images each. Each environmental stimulus was independently assessed 88 times, providing adequate data repetition to ensure statistical accuracy and stability in the mean scores of scene perception. Additionally, all volunteers completed the scoring of all images independently, thereby ensuring uniformity in evaluation criteria and minimizing between-group variability. Ultimately, 88 volunteers completed the scoring of all sample pictures, producing the environmental security score dataset for the study.

### *2.2. Extraction and Quantification of Visual Elements*

#### 2.2.1. Extraction of Visual Variables

The explanatory variables are visual elements primarily extracted via image semantic segmentation. Semantic segmentation constitutes a core task in computer vision, aiming to assign every individual pixel in an image to a predefined semantic category [22]. Unlike traditional image classification, which only identifies objects in the image, semantic segmentation categorizes each pixel, thereby providing a pixel-level understanding [23]. By applying semantic segmentation techniques to panoramic imagery, pixel-level urban features including roads, buildings, and green spaces can be systematically classified. This classification enables the systematic assessment of urban safety and comfort based on the identified features [24]. Street view image segmentation was conducted using the MIT ADE20K model with a ConvNeXt backbone [25], as well as a supplementary model based on segformer and trained with the Mapillary Vistas dataset [26]. ADE20K is a large-scale dataset for semantic segmentation, containing over 20,000 images divided into training, validation, and test sets. These images are densely annotated with 100 'thing' categories (e.g., vehicles, pedestrians) and 50 'stuff' categories (e.g., roads, sky), covering 89% of the pixels. Mapillary Vistas is a street view image dataset comprising 25,000 images, split into training, validation, and test sets. These images are densely annotated with 28 'stuff' categories and 37 'thing' categories, covering 98% of the pixels [27]. This study examines several key element categories, including the sky, trees, buildings, motor vehicles, and pedestrian areas [28]. The segmentation results for the datasets demonstrate these element categories and thereby satisfy the study's requirements (Figure 2).

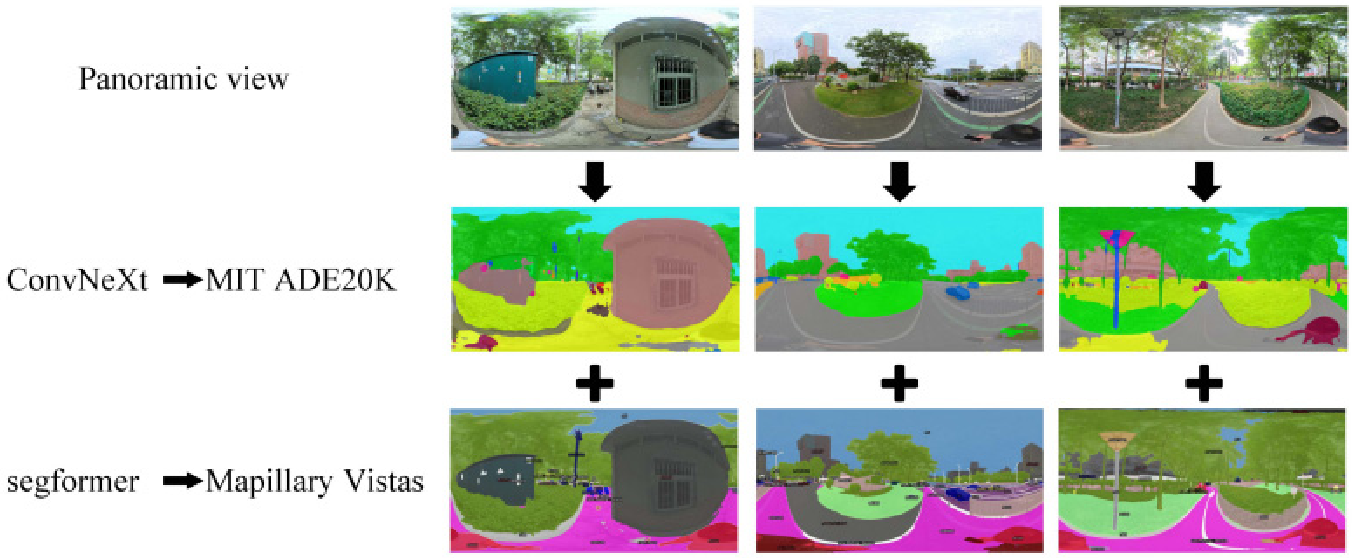



**Figure 2.** Extraction of visual elements.

#### 2.2.2. Quantification of Visual Variables

This study centers on the environmental safety perception score and employs a hybrid method that combines manual assessment and machine learning to conduct quantitative analysis on large-scale data. Deep learning technologies are employed to train models, thereby improving computational efficiency and resource utilization. Through its self-attention mechanism, as a deep learning model, the Transformer architecture can effectively capture long-distance dependencies in images, leading to significant improvements in segmentation accuracy. This architecture demonstrates superior performance in handling complex scenes and high-resolution images, further illustrating its effectiveness and robustness [29]. We constructed a dataset with 10,000 image comparison pairs, of which 8000 were allocated for training and 2000 for testing. The ConvNeXt model, built on the Transformer architecture, was selected for training. Training hyperparameters included a learning rate of 0.001, the Adam optimizer, a batch size of 20, and a training duration of 120 epochs. Cross-Entropy Loss was utilized as the loss function [30]. Once the training phase concluded, the model was applied to the test set, achieving an accuracy of 89.2%. Subsequently, all panoramic images of pocket parks were processed to compute their safety perception scores.

### *2.3. Construction of Environmental Safety Perception Model*

This study utilized the LightGBM algorithm to investigate the associations between environmental safety perception and visual cues [31]. We used a learning rate of 0.001, the Adam optimizer, a batch size of 20, and trained for 120 epochs. The validation split was 20% of the dataset. LightGBM is a highly efficient gradient boosting decision tree algorithm that achieves faster training by optimizing data processing efficiency. It prioritizes samples with large gradient variations while deemphasizing those with small variations, thus preserving model accuracy without unnecessary computational overhead. The algorithm employs a leaf growth strategy, where each iteration selects and splits the leaf node with the highest gain until the maximum number of splits is achieved. By capping the tree depth, LightGBM prevents overfitting and enhances model stability. Compared to traditional algorithms, LightGBM demonstrates superior performance in terms of training speed, memory efficiency, and accuracy, positioning it as one of the most efficient frameworks for gradient boosting tasks. Its high efficiency originates from optimized histogram algorithms and leaf growth strategies, which work together to substantially increase both training efficiency and memory utilization. Through its gradient boosting mechanism, LightGBM incrementally improves predictive performance by iteratively refining residuals. The algorithm excels in handling large-scale data, supports parallel computing and distributed learning, and is particularly well-suited for high-dimensional data scenarios [32]. Hyperparameter tuning of LightGBM, including learning rate, tree depth, and regularization parameters, significantly impacts the model performance [33].

### *2.4. Quantify the Impact of Visual Elements on Environmental Safety Perception Based on SHAP and PDP*

SHAP (SHapley Additive exPlanations) is a method rooted in Shapley values from cooperative game theory, enabling the analysis and interpretation of model predictions [34]. SHAP quantifies the contribution of each feature to the model's prediction and determines whether these contributions are positive or negative. PDP is employed to visually illustrate the marginal effect of one or two variables on the model's predictions. This technique involves computing the marginal effect of a specified variable by systematically varying its values while holding other variables constant. SHAP combines both global and local interpretability by providing insights into the overall model behavior and individual prediction contributions. This study integrates SHAP and PDP to assess how visual elements influence environmental safety perception. Because they provide both global and local interpretability, which is crucial for understanding the complex relationships between visual elements and safety perception. Other methods like LIME were considered but were less suitable for our high-dimensional data and complex models.

## 3. Results

### *3.1. Spatial Distribution and Assessment of Perception of Environmental Safety*

The urban development of Xiamen Island features a 'dual-core' structure: Siming District as the traditional central urban area and Luhui District as the emerging development zone. This development model has significantly shaped the urban fabric and public space quality of both areas, particularly evident in the elderly residents' ratings of park environment security.

The safety awareness scores of elderly residents were assessed in 29 pocket parks across Xiamen Island (Figure 3). Notably, elderly residents in Siming District exhibited consistently lower scores compared to those in Hulin District. Siming District, as Xiamen Island's historic core, comprises numerous aging residential communities. Parks 5, 8, 9, and 10, which scored between 4.60 and 5.83, are typically found within such communities. These low scores reflect persistent deficiencies in the hardware quality and management systems of these aging communities. In contrast, Hulin District, a rapidly developing area with new high-density residential and commercial mixed-use developments, contains high-scoring parks (e.g., 19, 20, 22–25, 28, and 29; scores of 6.60–7.17), illustrating successful urban planning outcomes. These high-scoring parks benefit from modern urban development principles, including well-designed hardware infrastructure and professional management, which together create high-quality and secure public activity spaces for elderly residents. These findings highlight the importance of urban planning in addressing the specific needs of elderly residents through well-designed facilities and effective management systems.

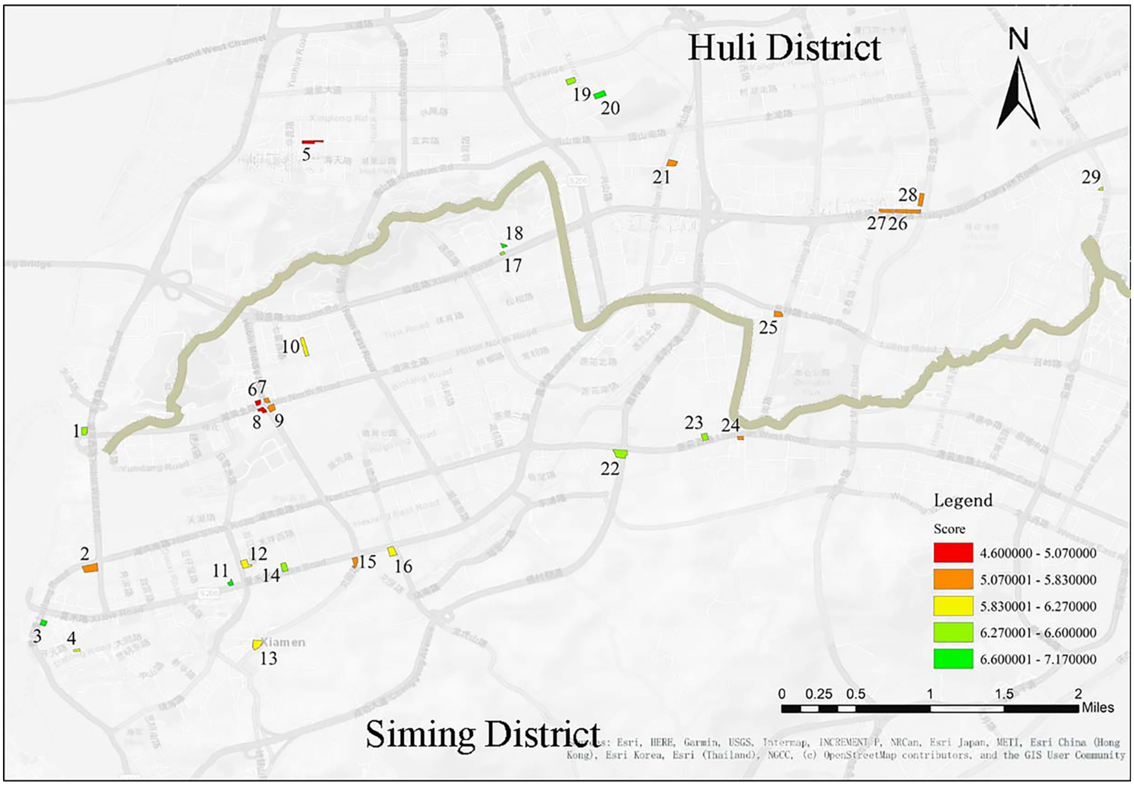
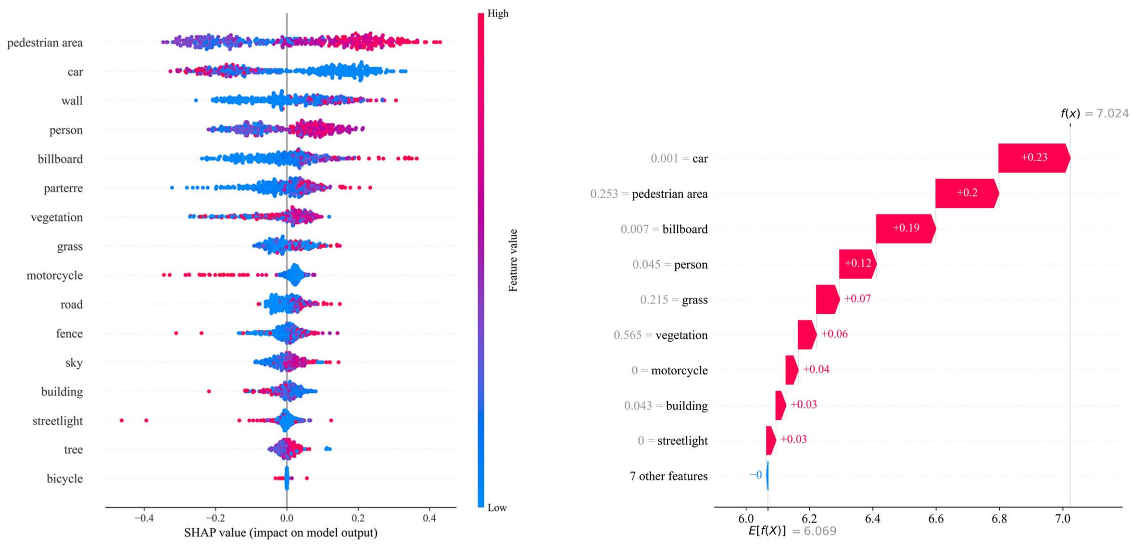



**Figure 3.** Environmental Safety Perception Distribution Characteristics of Elderly People's Pocket Parks on Xiamen Island.

### 3.2. SHAP Feature Contribution Results

Figure 4a demonstrates the effect of distinct visual elements on elderly individuals' environmental safety perception. The elements are ranked by their importance, with the horizontal axis representing the SHAP value (i.e., influence weight) of each element. Areas with larger width and higher density indicate stronger influence. The dots denote pocket park samples. Darker shades of red correspond to higher safety perception, while darker shades of blue indicate lower safety perception. The SHAP values for pedestrian areas exhibit a broad distribution, with a primary concentration in the positive region, suggesting that it exerts a strong positive effect on environmental safety perception. Augmenting walkable spaces and enhancing walking infrastructure can improve safety perception among elderly individuals [35]. Research on urban design indicates that narrow sidewalks are likely to negatively influence pedestrian perception, such as by restricting visual accessibility and movement comfort. Conversely, wider sidewalks are associated with an enhanced perception of space due to improved comfort and safety [36]. The car exhibits a significant influence in the graph, primarily through negative SHAP values. This suggests that the presence of vehicles significantly diminishes the environmental safety perception of the elderly. Vehicles moving outside pocket parks may induce anxiety among the elderly, who may have concerns about traffic accidents and safety [37]. Vehicle noise and exhaust emissions may negatively impact the health of the elderly, particularly their respiratory and cardiovascular systems, thereby reducing their comfort and sense of security in their environment [38,39]. Furthermore, vehicles parked in pedestrian zones can limit the mobility of the elderly, increasing their risk of collisions and subsequently diminishing their perceived environmental safety [40]. The SHAP values for walls exhibit a dispersed distribution, with some values in the positive range and others in the negative range. This dual distribution reflects the dual role of walls in shaping environmental safety perception. Specifically, low fences or flower beds that provide visual screening and psychological reassurance can enhance the elderly's sense of security.

In contrast, tall walls may block visibility, reduce spatial transparency, and thereby induce feelings of oppression and insecurity among the elderly [41]. Person presence correlates with improved environmental safety perception, as reflected by predominantly positive SHAP values. A low visitor count may indicate insufficient natural surveillance, allowing potential offenders to operate undetected and thus heightening feelings of insecurity, particularly among elderly individuals [42]. Excessive human gatherings can cause visual information overload, impairing elderly individuals' ability to interpret environmental cues and thus compromising their judgment of environmental safety [43]. Furthermore, excessive crowd density can induce psychological distress in elderly individuals, which may, in turn, impair their perceptual abilities [44]. Excessive crowd density may induce anxiety and unease in the older population, potentially compromising their perceptual abilities. Significantly, the positive effects of signage features suggest that they can enhance the older population's perception of environmental safety. Well-planned notice boards, which provide clear directional cues and location information, serve as effective tools for guiding older adults in navigating and utilizing spaces, ultimately boosting their sense of security [45]. Most of the SHAP values for parterre and vegetation are positive, indicating their relatively favorable contribution to environmental safety perception. While their overall contribution may be modest in comparison to other factors, their effect remains positive, contributing to the enhancement of environmental safety perception. A well-designed flower bed layout and appropriate vegetation density not only enhance the visual appeal of the environment but also contribute to psychological comfort. Furthermore, their isolating and buffering functions mitigate external disturbances, thereby improving the sense of security among elderly residents [46,47]. The SHAP values of elements such as grass, motorcycles, roads, fences, sky, buildings, streetlights, trees, and bicycles are relatively small, suggesting a minimal contribution to environmental safety perception. Greening, however, positively reinforces the environmental safety of the elderly [48,49]. Trees on pedestrian paths enhance the perceived attractiveness and safety of the walking environment, underscoring the significance of infrastructure quality. However, the presence of trees may not always directly enhance perceived safety, depending on specific circumstances [50]. Specifically, the SHAP values of grass and streetlight are predominantly positive, suggesting they exert a mild positive influence on safety perception. Conversely, the SHAP values of motorcycles and roads often display negative contributions, potentially undermining safety perception. Furthermore, overgrown vegetation may conceal hazards such as uneven terrain or obstacles, thereby raising the likelihood of accidents.




(a) SHAP Summary Plot (b) SHAP**waterfall plot**

**Figure 4.** The influence of visual elements on the environmental safety perception of the elderly.

Figure 4b illustrates the specific contributions of each visual element to the model output, reflecting their impact on environmental safety perception. The model output value f(x) = 7.024, which reflects a relatively high environmental safety perception score for the pocket park. The contribution values of each element, listed in the figure, indicate their impact on the model output: positive values represent a positive influence, whereas negative values signify a negative influence. While the contribution value of the car to the model output is +0.23 (denoted by the red arrow in the figure), this positive value represents the absolute magnitude of its negative impact, indicating that vehicles significantly reduce perceived environmental safety. This aligns with the global interpretation that vehicles negatively affect safety perception [51]. The pedestrian area contributes +0.2 to the model output, suggesting that its width and accessibility significantly enhance the environmental safety perception of the elderly. This finding is consistent with the global interpretation that pedestrian zones positively affect safety perception, underscoring their importance in pocket park design. The billboard contributes +0.19 to the model output, likely due to its clear and well-designed informational content, which effectively enhances environmental safety perception among the elderly. The person contributes +0.12 to the model output, increasing social interaction, vitality, and perceived safety among the elderly. Grass (+0.07) and vegetation (+0.06) positively influence environmental safety perception due to their appropriate quantity and well-planned layout. This aligns with the global interpretation that grassland and vegetation positively influence safety perception [52]. While elements such as motorcycles, buildings, and streetlights have smaller contribution values (e.g., streetlights contribute +0.03), they still positively influence environmental safety perception, particularly by enhancing nighttime or low-light security [53].

This study focuses on the analysis of the internal environment of pocket parks, particularly examining the impact of visual elements on the environmental safety perception of the elderly. Based on relevant literature and on-site investigations, six key visual elements were identified for in-depth research: pedestrian area, car, person, billboard, vegetation, and grass. The vegetation includes various plant types above the ground, such as trees, shrubs, grasslands, hedges, and shrub forests. They have a certain obstructive effect on the vision of the elderly. In contrast, grassland is mainly composed of low-growing herbaceous plants and covers the ground surface, and its effect on vision obstruction is not significant. Therefore, in this study, it is divided into two different indicators.

### *3.3. Univariate Key Visual Elements Contribute to Shaping Elderly Individuals' Perception of Environmental Safety*

Figure 5a–f illustrates the quantitative characterization of the main effects of six key visual elements using partial dependency plots (PDPs). All curves lie within a 95% confidence interval, with the horizontal axis denoting the pixel proportion of the elements and the vertical axis denoting the safety perception score of the elderly. The blue solid line, representing the Partial Dependence Curve (PDC), illustrates the partial dependence of the model's predictions on a specific feature. It demonstrates how the model's predictions are affected by variations in the feature. The blue shaded area indicates the 95% confidence interval, reflecting the statistical uncertainty of the curve. A narrow shaded area indicates high consistency in the model's response, while a wide shaded area suggests significant variability, likely due to feature interactions or data sparsity. The red dots indicate the distribution of actual sample data, with their positions aligned with the feature values in the dataset. Observing their density helps identify regions where sufficient data exists to support reliable model predictions. For instance, a dense cluster of red dots in a specific interval implies higher reliability of model predictions within that area. The pedestrian area exerts a significant nonlinear effect on the prediction results. Once the area exceeds a certain threshold (approximately 0.18–0.22), the larger the area, the higher the prediction result, indicating an optimal area range or a positive impact after the critical point. Car count is inversely related to the prediction results; a small number of vehicles leads to a marked decrease in results, which remain low. Overall, vehicles negatively impact the target variable. Person exhibits a threshold effect on the prediction results. When density reaches approximately 0.040, the results significantly improve and stabilize at a high level, suggesting better performance of the target variable at this density. Billboard count may positively impact the prediction results up to a point, but exceeding approximately 1.0% may lead to a decline, indicating an optimal number of signboards. Vegetation density has a nonlinear influence, with an optimal range at approximately 0.30. Too low or too high densities may negatively impact the results. The grass area may initially decrease the prediction results but turn positive once the area reaches approximately 0.07, indicating a beneficial effect after a certain scale.

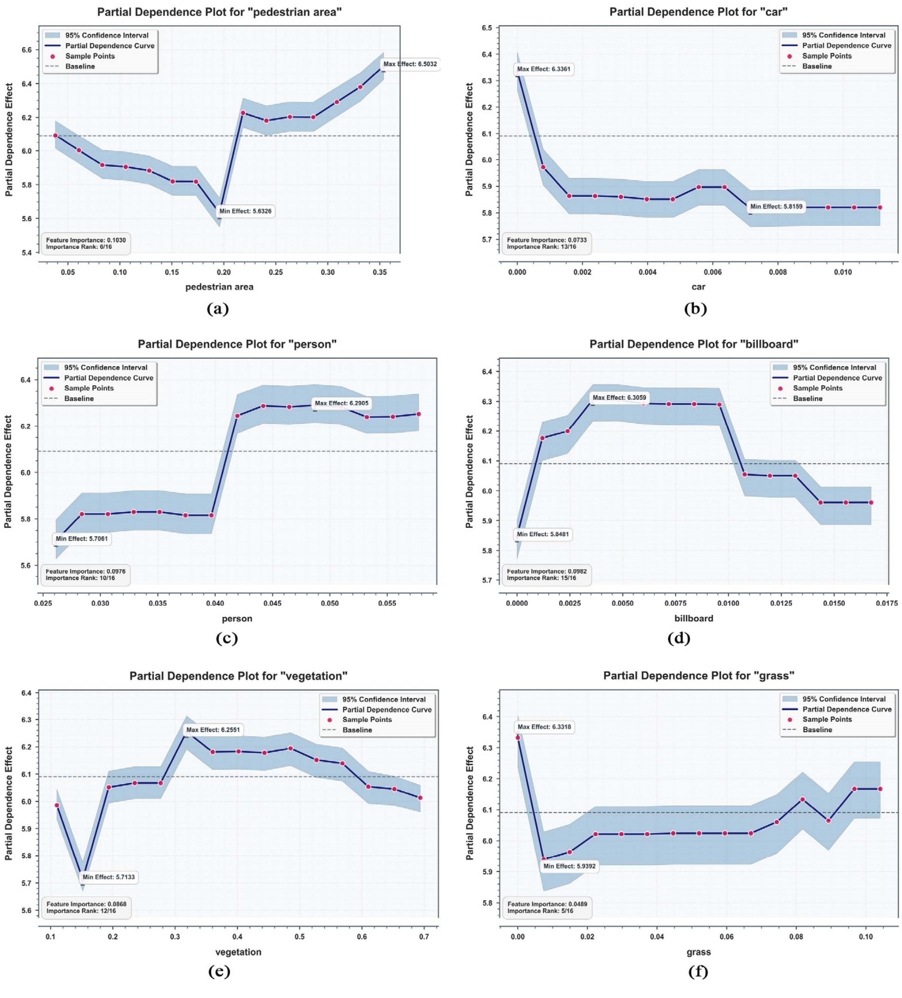



**Figure 5.** Main effect analysis of univariate PDP on the environmental safety perception of the elderly. (**a**) Partial Dependence Plot for pedestrian area; (**b**) Partial Dependence Piot for car; (**c**) Partial Dependence Plot for person; (**d**) Partial Dependence Piot for billboard; (**e**) Partial Dependence Plot for vegetation; (**f**) Partial Dependence Plot for grass.

### *3.4. Bivariate Key Visual Elements Contribute to Shaping Elderly Individuals' Perception of Environmental Safety*

Figure 6a–o depicts pairwise analyses of six key visual elements. The color intensity indicates the elderly's safety perception scores, with the color gradient reflecting the vertical axis values (or color bar). The darker the color, the higher the perceived safety in the corresponding area, while the lighter the color, the lower the perceived safety. Therefore, the optimal combination range and risk areas are visually distinguishable based on color variations. According to the magnitude of partial dependence, the 15 visual element combinations are categorized into three influence magnitudes: high, medium, and low, as presented in Table 1. The classification was based on the magnitude of the partial dependence range, which was calculated as the difference between the maximum and minimum partial dependence values for each element combination. The specific ranges for high-, medium-, and low-impact amplitudes are as follows:

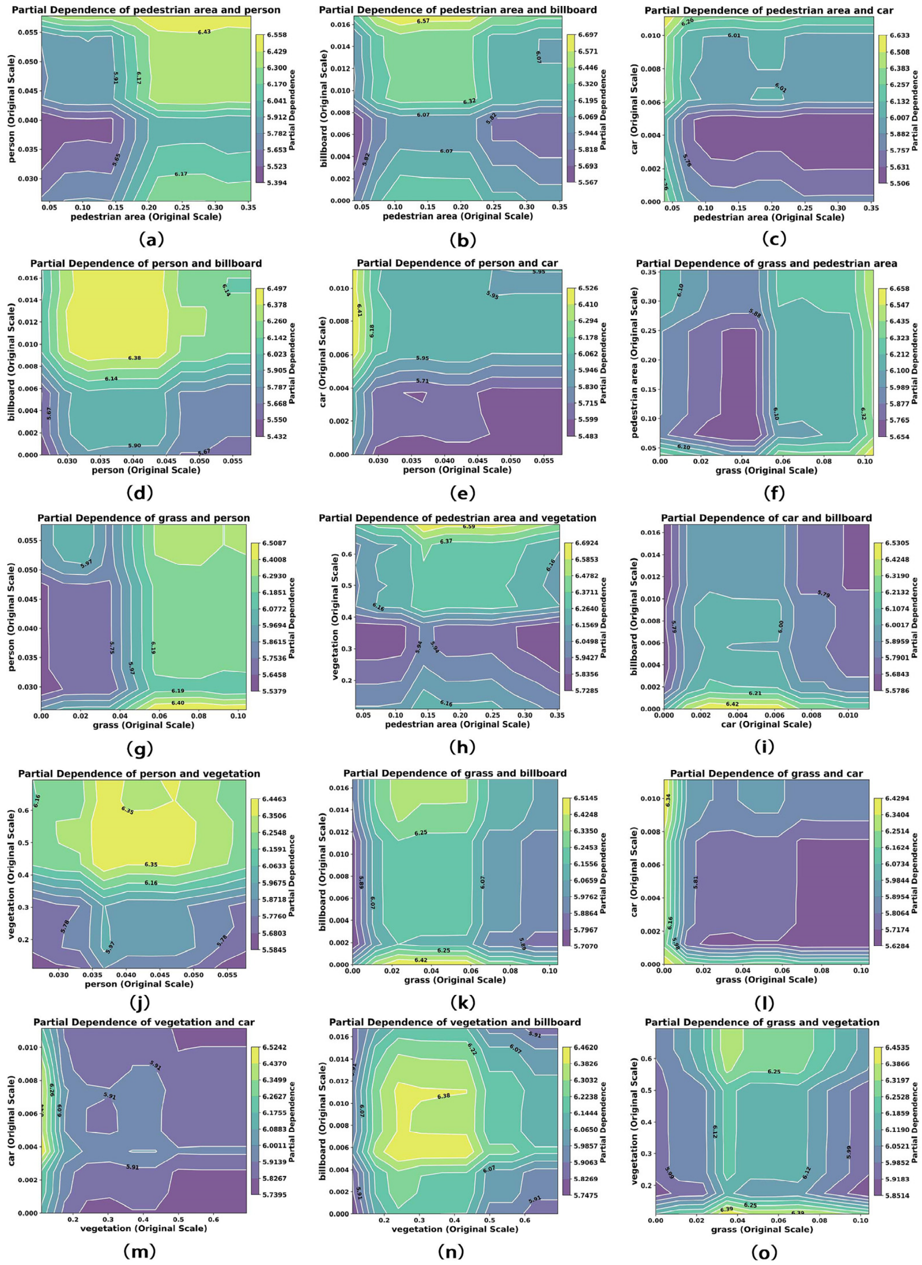



**Figure 6.** Analysis of the regulatory mechanism of interactive PDP on the environmental safety perception of the elderly. (**a**) Partial Dependence of pedestrian area and person; (**b**) Partial Dependence of pedestrian area and billboard; (**c**) Partial Dependence of pedestrian area and car; (**d**) Partial Dependence of person and billboard; (**e**) Partial Dependence of person and car; (**f**) Partial Dependence of grass and pedestrian area; (**g**) Partial Dependence of grass and person; (**h**) Partial Dependence of pedestrian area and vegetation; (**i**) Partial Dependence of car and billboard; (**j**) Partial Dependence of person and vegetation; (**k**) Partial Dependence of grass and billboard; (**l**) Partial Dependence of grass and car; (**m**) Partial Dependence of vegetation and car; (**n**) Partial Dependence of vegetation and billboard; (**o**) Partial Dependence of grass and vegetation.

**Table 1.** Key Visual Elements Grouped by Adjusted Interaction Influence.

| Feature Pair | Calculation Range (Maximum PD–Minimum PD) | Classification of Impact Amplitude |
|---|---|---|
| grass_vegetation | 0.6021 | Low |
| vegetation_billboard | 0.7145 | Low |
| vegetation_car | 0.7847 | Low |
| grass_car | 0.801 | Medium |
| grass_billboard | 0.8075 | Medium |
| person_vegetation | 0.8618 | Medium |
| car_billboard | 0.9519 | Medium |
| pedestrian area_vegetation | 0.9639 | Medium |
| grass_person | 0.9708 | Medium |
| grass_pedestrian area | 1.004 | High |
| person_car | 1.043 | High |
| person_billboard | 1.065 | High |
| pedestrian area_car | 1.127 | High |
| pedestrian area_billboard | 1.13 | High |
| pedestrian area_person | 1.164 | High |

High-Impact Amplitude: $\geq$0.98;

Medium-Impact Amplitude: 0.79 to 0.97;

Low-Impact Amplitude: <0.79.

The high-impact amplitude is shown in Figure 6a–f. Feature combinations in this group demonstrate the most significant impact on safety perception in model predictions, characterized by the largest partial dependence range ($\geq$0.98). These combinations possess the strongest capacity to influence the safety perception of elderly individuals [54]. Significant differences in elderly safety perception are observed under varying feature combinations, aligning closely with the model's predictive outcomes. The features of the high-bias dependent range group, which primarily centers on pedestrian areas and person, form a strong synergy with other positive features such as grass, car, and billboard. This synergy indicates that when these elements coexist, they mutually reinforce positive outcomes on elderly safety perception. Among these combinations, optimal feature combinations are typically characterized by high intensities of relevant features. This strongly supports the "Street Eye" theory and highlights the importance of promoting the creation of active [55], accessible, and green urban environments. When these elements coexist and are well managed, their synergistic potential can enhance positive influences to maximize perceived safety. Conversely, the risk areas associated with these combinations tend to occur when all related characteristics remain at low levels. This indicates that a lack of human activities, restricted pedestrian space, and inadequate green infrastructure or urban vitality can result in a significant decrease in perceived safety [56]. This phenomenon is particularly pronounced among the elderly, whose physical and mental vulnerabilities heighten their sensitivity to environmental risks.

The influence amplitude, as visualized in Figure 6g–l, demonstrates that the characteristics within this group exert a moderate yet statistically significant impact on safety perception. This relationship exhibits a partial dependence range of 0.79 to 0.98. Combinations within this moderate dependence range reflect diverse interaction patterns, including synergistic and compensatory effects. For example, optimal safety perception often emerges when positive features such as grass, person, car, and billboard are present at relatively high levels. These interactions effectively enhance perceived safety; however, their impact typically remains less pronounced than that of the high-range group. For instance, the interaction between grass and car illustrates that when grass levels are low, the presence of cars contributes significantly to safety perception. This occurs as cars act as compensatory elements by signaling urban activity and accessibility, thereby enhancing the sense of security in undergreened settings [57]. However, the compensatory effect of vegetation does not universally enhance safety perception. In certain scenarios, dense vegetation—particularly in areas with limited human activity or pedestrian functionality—can negatively influence safety perception. This highlights that vegetation density and management quality significantly impact safety perception; overly dense or poorly maintained vegetation can become a safety hazard. This phenomenon is especially prevalent among the elderly, given their heightened sensitivity to environmental safety due to physical and cognitive limitations. Consequently, public space design and management should holistically integrate these factors to enhance the safety perception of elderly individuals.

Figure 6m–o illustrates the relative influence of low-amplitude factors on safety perception. These combinations, which often involve vegetation, demonstrate counterintuitive negative trends under specific conditions. Vegetation's impact on safety perception is complex: its optimal contribution occurs at low or medium levels when paired with high-level urban features (e.g., billboards or cars), potentially enhancing urban vitality and visibility. Conversely, high vegetation levels coupled with low levels of other urban features may create risk zones. This highlights that excessive vegetation, especially without complementary positive safety signals, can be perceived as a safety hazard, significantly reducing perceived safety [58]. This indicates that in urban design, the types, densities, and layouts of vegetation must be carefully controlled to mitigate their adverse effects on perceived safety. Evidence shows that vegetation density significantly influences people's perceived tendency to engage in activities. A more pronounced sense of community hierarchy in vegetation layouts can reduce overly intense behavioral tendencies and encourage a broader range of human activities. Furthermore, integrating vegetation communities with rest facilities enhances positive emotions among users and fosters greater social engagement. In urban design, vegetation should strike a balance between fulfilling ecological functions and addressing its influence on human behavior and emotional responses [59].

## 4. Discussion

This study employed an interpretable machine learning model to quantify and investigate the influence of pocket parks' visual elements on the environmental safety perception of the elderly. The results confirmed previous theories while revealing complex nonlinear relationships and interaction mechanisms between the elements. These findings contribute to a scientific basis for urban micro-space planning and design, particularly in settings involving aging populations.

### *4.1. The Nonlinear Impact Dynamics of Key Visual Elements*

Unlike traditional research that often simplifies elements like greening and human flow into single positive or negative factors, this study identifies the complex and threshold-dependent nature of their contributions using SHAP and PDP analysis. The core roles of "safe space" and "social vitality" are as follows: Research indicates that pedestrian area and person are the two most significant factors for improving the sense of safety among elderly pedestrians. This aligns with Jacobs' "Eyes on the Street" theory: moderate crowd activities provide natural surveillance, thereby enhancing the sense of security in the space. The spacious and clear pedestrian area not only ensures ease of mobility and potential escape routes for the elderly but also promotes a psychological perception of "controllability" and "accessibility," thereby significantly reducing anxiety caused by uncertainty. PDP analysis further quantified its threshold effect: when the proportion of pedestrian area exceeds approximately 0.20 and the density of human vision exceeds 0.04, the sense of security rises to a relatively high and stable level. This suggests that successful pocket park design must prioritize ensuring sufficient walking and activity spaces, while creating a social environment that attracts moderate human activity.

The overwhelming negative impact of traffic threats: Cars are identified as the strongest negative contributor to reduced safety perception. Even if the visual proportion of cars is relatively low, their presence leads to a sharp decline in safety perception. This indicates that the elderly, as a vulnerable group in traffic environments, are highly sensitive to potential traffic accident risks. The noise, exhaust fumes, and visual intrusion generated by vehicles jointly disrupt the peaceful and safe atmosphere of pocket parks, contradicting the restorative environment advocated by the Stress Relief Theory (SRT). This finding highlights that effective physical isolation or visual buffering measures are essential in pocket park site selection and design to minimize traffic disruption as much as possible.

The “double-edged sword” effect of natural elements: Research confirms the positive role of vegetation and grass in safety perception, aligning with the Attention Restoration Theory (ART), which highlights the natural environment’s contribution to psychological recovery. However, this study reveals the nonlinear nature of these elements’ influence. The PDP curve shows that vegetation has an optimal density range (approximately 0.30). If density is too low, ecological benefits remain limited; if it is too high, it may create a sense of insecurity by obstructing views and providing hiding spots. This challenges the traditional notion that “the more greenery, the better.” Designers must balance aesthetic value, ecological benefits, and safety requirements by, for example, adopting plant configurations with optimal spacing, controlling shrub height, and ensuring visibility within forest understories.

### *4.2. The Interaction, Coordination and Restraint Mechanism of Visual Elements*

The interplay of visual elements was analyzed via bivariate PDP analysis in this study. By moving beyond single-element limitations, the analysis revealed the synergistic amplification effect and the intricate trade-offs of mutual restraint among elements, representing a key research insight.

Synergistic Amplification of High-Impact Combinations: Combinations like pedestrian area with pedestrian activity and pedestrian area with car presence show strong synergistic effects among positive elements. When spacious walkable spaces are paired with moderate social activity, safety perception peaks. This highlights how physical space design and social vitality interact to form the foundation of elderly safety perception. Notably, a limited vehicular presence in such zones—reflecting accessibility or regional vitality—exerts minimal negative impact due to the buffering effect of positive factors.

Complex Trade-Offs of Medium- and Low-Impact Combinations: The interactions between vegetation and other elements display the greatest complexity. For example, in sparsely used zones, high-density vegetation correlates with reduced safety perception. By contrast, in densely populated areas, vegetation density has negligible negative effects. This underscores the importance of natural surveillance, which mitigates insecurity caused by visual obstructions. These findings provide implications for park management: sparsely used zones should prioritize vegetation permeability and maintenance, while crowded zones may benefit from increased greenery to enhance ecological comfort.

### *4.3. The Theoretical and Practical Significance of the Research*

This study advances both methodological frameworks and practical insights.

Methodological Contribution: The research establishes a closed-loop framework of “data-driven modeling—interpretive analysis—design optimization.” By combining panoramic imagery, deep learning semantic segmentation, and explainable AI models (SHAP, PDP), this study transforms subjective environmental perceptions into measurable and interpretable indicators. This approach enhances research rigor and provides a robust analytical framework for studying the humanistic design of future urban environments.

The findings can be directly translated into design guidelines for pocket parks:

(1) Optimize pedestrian pathways: Create wide, continuous, and barrier-free walking areas using slip-resistant materials like EPDM rubber floors. Design interconnected paths to form a circular or networked layout, minimizing narrow or sharp turns for safety.
(2) Restrict vehicular access: Establish no-parking zones with clear signage and surveillance. Install safety barriers, such as greenbelts or bollards, to shield parks adjacent to roads, reducing vehicle threats and promoting low-carbon travel.
(3) Enhance social space: Place rest seats and social facilities in safe, sheltered areas to accommodate the physical needs and social preferences of users. These arrangements foster interaction and community engagement.
(4) Design effective signage: Position notice boards at prominent locations (e.g., entrances and along walkways) to convey park maps, facility details, and event schedules. Include health-related information boards to meet educational needs while maintaining visual clarity.
(5) Select appropriate vegetation: Plant tall trees for shade and opt for low-growing, non-toxic plants. Prioritize layered vegetation layouts with transparency for safety. Regular maintenance ensures cleanliness and aesthetic appeal.
(6) Plan grassland areas: Design grassy zones based on park scale and functionality. Use durable, soft grass species (e.g., ryegrass) and incorporate seating or pathways along edges to enhance accessibility.

### *4.4. The Limitations of the Research and Future Prospects*

Despite meaningful findings, this study has limitations. The research focuses on Xiamen City, a unique coastal region with distinct cultural, climatic, and urban characteristics [60]. These factors may influence the generalizability of the conclusions. The applicability of research findings may vary across countries with differing levels of economic development, public safety, political systems, and population well-being. Future research will therefore aim to address these limitations and extend the applicability of the findings to diverse contexts. Secondly, the study employs static panoramic images as the primary environmental evaluation tool. While intuitive, this approach fails to account for dynamic environmental changes, such as atmosphere variations across time of day, weather conditions, and seasonal transitions. Additionally, it excludes multi-sensory environmental elements like sound and smell, which could significantly impact the perception of safety among the elderly. The aging population is heterogeneous, encompassing differences in age, physical and mental health, socioeconomic status, life experiences, and education. Such diversity likely complicates the mechanisms influencing their safety perception [61]. However, this study provides only limited insight into these variations.

The study focuses on pocket parks within urban micro-renewal initiatives due to their significant role in enhancing the mental well-being of elderly residents. While pocket parks lack the expansive open spaces, low population density, and walkability of larger parks, their compact size and high accessibility create unique challenges and opportunities. As integral components of urban green spaces, pocket parks directly influence the quality of life of urban residents, particularly the elderly, through their layout and design. Pocket parks serve dual functions: they provide urban residents with access to nature while fostering community interaction, mitigating the urban heat island effect, and enhancing urban aesthetics. Although smaller in scale, pocket parks are indispensable elements of urban renewal and community building due to their high-density distribution and accessibility.

Given the aforementioned limitations, future research could explore the following directions in greater depth for operational feasibility:

(1) Cross-regional and cross-cultural comparative studies could be conducted by selecting cities or regions with distinct characteristics. This would allow for a more rigorous examination of the universality and boundary conditions of the current findings.
(2) Dynamic video data and time-series image analysis could be employed to systematically capture and analyze environmental dynamics, including changes in pedestrian and vehicular flows, diurnal lighting variations, and seasonal landscape shifts. This would enhance the understanding of real-time safety perceptions among the elderly.
(3) A multi-sensory environmental perception model could be developed by integrating multi-source data collection techniques. These techniques include in-depth field questionnaire surveys, continuous behavioral observations, physiological index measurements (e.g., heart rate variability and skin conductance response), and wearable sensor data. This integrated approach would help reveal the complex relationships between environmental characteristics and perceived safety.
(4) Differentiated studies targeting subgroups of the elderly (e.g., advanced-age vs. young-old populations, those with varying health conditions, and individuals from diverse socio-economic backgrounds) could be conducted. This would enable a deeper analysis of their distinct safety concerns and environmental preferences, thereby offering robust scientific evidence and design insights for developing inclusive, tailored, and diversified age-friendly environments.

## 5. Conclusions

This study examines environmental safety issues in pocket parks within urban aging contexts, employing interpretable machine learning methods for a systematic quantitative analysis of visual elements influencing older adults' environmental safety perception.

Our findings uncover three core principles governing elderly safety perception, derived from field investigations and data analysis:

(1) Key positive factors include sufficient walkable areas, which ensure safe and barrier-free mobility for the elderly, and moderate group activities, which foster community vitality and enhance perceived safety.
(2) The relationship between natural elements and safety perception is nonlinear. While moderate greening improves environmental quality and reduces stress, excessive vegetation can obstruct vision, diminish path clarity, and introduce safety risks.
(3) Complex synergistic relationships exist between visual elements. For instance, the combination of spacious pedestrian areas, vibrant social activity, and optimal greening yields the highest safety perception among the elderly.

This research not only offers insights into older adults' environmental perception but also provides an interpretable analytical framework and practical guidance for urban planners and designers. By emphasizing the importance of overall environmental coordination, the study highlights the need to transition from isolated optimization of design elements to the creation of comprehensive, people-oriented spaces that encourage social interaction, manage natural elements effectively, and minimize traffic threats. Under the dual trends of globalization and aging populations, these findings carry significant theoretical and practical value for advancing the refinement and humanization of urban public spaces.

**Author Contributions:** S.W. (Shengzhen Wu), Conceptualization; Supervision; Validation; Writing—original draft; Writing—review and editing. S.W. (Sichao Wu), Writing—original draft; Validation; Investigation. J.C., Writing—original draft; Data curation; Resources; Validation. C.P., Writing—original draft; Investigation; Software. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by (1) Fujian Provincial education System Philosophy and Social Science Research Project (JAS24049). (2) Research Project of Higher Education Science Research Laboratory of Fujian Higher Education Association in 2024 (24FJSYZD038).

**Institutional Review Board Statement:** Ethical review and approval were waived for this study, due to this study only invited the elderly to rate the panoramic images, but did not involve questionnaires or human experiments.

**Informed Consent Statement:** This study only invited 88 elderly individuals to assist in the scoring process. It did not involve human experiments, so no informed consent form was required.

**Data Availability Statement:** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Conflicts of Interest:** The authors declared no potential conflicts of interest with respect to the research, author-ship, and/or publication of this article.

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