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Impact of Physical Features on Visual Walkability Perception in Urban Commercial Streets by Using Street-View Images and Deep Learning

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Abstract: Urban commercial streets are a crucial component of urban life, serving as the central hubs of commercial activity and providing vital spaces for both residents and visitors to engage in various activities. Walkability is commonly used as a key indicator of environmental quality, playing a significant role in improving residents' health, community interaction, and environmental quality of life. Therefore, promoting the development of a high-quality walking environment in commercial districts is crucial for fostering urban economic growth and the creation of livable cities. However, existing studies predominantly focus on the impact of the built environment on walkability at the urban scale, with limited attention given to commercial streets, particularly the influence of their physical features on walking-need perceptions. In this study, we utilized Google Street-View Panorama (GSVP) images of the Tenjin commercial district and applied the Semantic Differential (SD) method to assess four walking-need perceptions of visual walkability perception, including usefulness, comfort, safety, and attractiveness. Additionally, deep-learning-based semantic segmentation was employed to extract and calculate the physical features of the Tenjin commercial district. Correlation and regression analysis were used to investigate the impact of these physical features on the four walking-need perceptions. The results showed that the different walking-need perceptions in the Tenjin commercial district are attractiveness > safety > comfort > usefulness. Furthermore, the results show that there are significant spatial distribution differences in walking-need perceptions in the Tenjin commercial district. Safety perception is more prominent on primary roads, all four walking-need perceptions in the secondary roads at a high level, and the tertiary roads have generally lower scores for all walking-need perceptions. The regression analysis indicates that walkable space and the landmark visibility index have a significant impact on usefulness, street cleanliness emerges as the most influential factor affecting safety, greenness is identified as the primary determinant of comfort, while the landmark visibility index exerts the greatest influence on attractiveness. This study expands the existing perspectives on urban street walkability by focusing on street-level analysis and proposes strategies to enhance the visual walkability perception of commercial streets. These findings aim to better meet pedestrian needs and provide valuable insights for future urban planning efforts.

Keywords: commercial streets; physical features; visual walkability perception; street-view images; deep learning

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1. Introduction

Commercial districts are one of the most frequently utilized spaces for social interactions and public life among urban residents [1]. These areas play a key role in economic activity by creating job opportunities through the concentration of commercial facilities [2]. In addition to fulfilling daily shopping, leisure, and consumption needs, commercial streets provide urban residents with ideal spaces for relaxation and entertainment activities [3]. Furthermore, commercial streets play a vital role in fostering local community vitality by encouraging face-to-face interactions among customers and pedestrians [4]. High-quality urban street environments also contribute significantly to enhancing residents' well-being [5], life satisfaction [6], and community cohesion [7]. Thus, building a high-quality urban commercial street environment is not only the key to urban image building and economic development but also an important way to improve residents' quality of life and achieve sustainable development.

The concept of walkability was first introduced in the late 1990s in transportation studies in the United States. Walkability covers all aspects of the built environment related to pedestrian transportation [8]. Better service facilities, higher landscape environment quality, diversified land use, and convenient travel paths all improve street walkability [9]. Many studies have shown that walkable street environments benefit both public health and environmental sustainability [10]. An environment with high walkability can reduce the sedentary behaviors of residents, increase physical activity levels, and improve health status. Relevant studies point out that walkable communities help reduce motor vehicle speeds, traffic volumes, and unsafe behaviors [11,12]. Violent crime and burglary are generally less likely to occur in neighborhoods with good walking conditions [13]. Additionally, walkable streets can promote economic prosperity in communities and society [14]. As hubs of economic activity, commercial districts attract people who may consume or need services. Therefore, a walkable environment in commercial areas may increase visitor numbers and spending [15]. It has important implications for enhancing the attractiveness of neighborhoods, extending customer dwell times and consumption willingness, and promoting the development of the urban economy. Studies confirm that greater satisfaction with pedestrian environments correlates with longer stays in commercial areas, which increases the likelihood of purchasing decisions [16]. Furthermore, features of a walkable environment have a positive impact on the per-capita sales of individual businesses [17]. Given this background, planners and scholars increasingly emphasize that the quality of pedestrian environments in commercial areas significantly affects their stability and sustainability. While walkability offers numerous benefits, it is also important to consider potential challenges for residents arising from increased street or neighborhood attractiveness. For instance, the higher walkability of commercial districts may lead to an increase in the likelihood of conflicts between pedestrians and vehicles, therefore raising the risk of pedestrian collisions [18]. Over-commercialization may also diminish the cultural identity and sense of belonging of locals [19]. Furthermore, as more visitors are drawn to these neighborhoods, the competition for shared public resources, such as parking spaces, parks, and public transit, may intensify, impacting residents' access to these amenities. Acknowledging and addressing these potential drawbacks is essential for planners and policymakers to ensure that the benefits of walkable environments are equitably distributed while minimizing unintended consequences for local communities.

In early studies, Gehl [18] described the quality of outdoor spaces needed for walking. Based on this study, related scholars have assessed walkability by designing vocabularies related to walkability and constructing evaluation systems [20,21], such as the Pedestrian Environment Review System, the Neighborhood Environment Walkability Scale, and Pedestrian Level of Service [22] methodology. Rosenberg et al. [23] used NEWS-Y to study the

relationship between U.S. neighborhood environments and adolescents' perceptions of walkability, finding that traffic safety, aesthetics, pedestrian or bike facilities, land-use mix, and the overall environment were positively associated with perceived walkability. In China, Cerin et al. [24,25] used NEWS and NEWS-A to study the impact of the built environment on perceived walkability among older adults in Hong Kong, identifying service accessibility and pedestrian and vehicular traffic as significantly related factors. However, these methods rely heavily on individual perceptual variables, resulting in one-sided assessments of the walking environment. Due to the high cost of this evaluation method, researchers can only conduct case studies on limited neighborhood areas. In recent years, related studies have utilized computer-assisted audits based on urban big data, such as Geographic Information System (GIS), to measure macro-level walkability in the city, country, or state. Researchers attempt to combine these objective attributes into a single walkability index to evaluate the degree to which a built environment supports walking. These macro-level attributes include intersection density, population density, and land-use diversity [26–28]. Walk Score, as a commonly used tool, is applied to analyze street walkability in various countries and regions [29]. These computer-assisted audits, which are based on urban big data, overcome the limitations of small sample sizes in manual assessments, providing opportunities for large-scale walkability evaluation. However, walkability as a complex concept is influenced by both objective environmental factors and subjective perceptions [30]. The physical features of a street can influence people's perception of the environment, therefore affecting their actual walking behavior and willingness to walk. The walkability index that relies heavily on macro-environmental features often overlooks the impact of street-level characteristics on walkability perception. Relevant scholars have suggested that walkability can be broadly perceived through four aspects: usefulness, safety, comfort, and attractiveness [31,32]. Usefulness reflects the motivating factors for walking, which may be influenced by factors such as destination accessibility and land-use diversity [33]. In addition, perceived walking barriers, such as physical obstacles, impassable land uses (gated communities), psychological barriers (overly wide roads), and environmental colors can affect pedestrians' perception of usefulness. Lynch et al. pointed out that color plays an important role in the recognition of spatial elements such as paths, landmarks, and edges in The Image of the City [34]. Safety refers to whether the street environment appears free from crime and traffic accidents, which is often associated with visual elements such as graffiti, litter, and abandoned buildings. A study shows that obstructed sightlines can increase fear of crime [35]. Wu et al. measured pedestrian safety perceptions using walkability, spatial enclosure, visual permeability, and vitality [36]. Traffic factors, such as motor vehicles and bicycles on the streets, also affect pedestrians' sense of safety in the street environment [37]. Comfort refers to whether the street environment enhances pedestrians' walking experience, which is closely related to factors such as street furniture, sidewalk conditions, urban design amenities, and accessibility features. Some scholars have explored the relationship between comfort and built environment factors such as street greening [38,39], street openness [40], and street facilities [41]. Attractiveness refers to the sensory and psychological enjoyment that pedestrians experience while walking in a particular environment [32]. with the aesthetic appeal, interest, and activity level of the street environment influencing pedestrians' perception of attractiveness. Some factors that may contribute to an attractive environment include street greening, historical or unique architecture, pedestrian traffic, and mixed land use. Moreover, due to differences in regional economic development and social-cultural backgrounds, pedestrians' perceptions of walking needs vary significantly across different areas [42,43]. A study comparing the perceptions of walking needs between pedestrians in Bangkok and Nagoya found that safety was regarded as a higher priority in Bangkok. This could be attributed to the poorer

street conditions in Bangkok, where narrow sidewalks and lower cleanliness levels create greater concerns [44].

With the development of computer technology and crowdsourced mapping services, fully accessible Street-View Image (SVI) data provides high-resolution, real-world, and street-level image data for studying urban street built environments [45]. Compared to on-site surveys, SVI offers a cost-effective and time-saving method for large-scale assessment [46]. Consequently, SVI is widely applied in community environment evaluations [47–50] and has become a primary data source in urban studies, providing an opportunity to evaluate the built environment at a micro level on a large scale, for example, identifying the structural components of the landscape [51], evaluating sky openness [52], and measuring street greenery and physical activity levels [53]. Some scholars have utilized SVI data to explore the impact of streetscape elements on public perception [54,55]. Visuals are the primary way for people to perceive their surroundings. Zhou et al. introduced the concept of visual walkability based on street-view images and proposed the visual walkability index as a quantitative measure for evaluating visual walkability [56]. Li et al., based on the hierarchy of walking needs, introduced the concept of visual walkability perception to represent whether the built environment visually encourages walking. They explored the influence of visual elements on walking-need perceptions by using street-view images, virtual reality, and deep-learning techniques [34,57].

In summary, the foundation for constructing high-quality urban commercial streets is the use of an effective approach to measuring visual walkability perception and the physical features of these streets. In addition, exploring the impact of commercial street physical features on visual walkability perception based on the public's walking needs has great significance in both theoretical and practical terms. As shown in Figure 1, this study applies semantic segmentation and Semantic Differential (SD) methods based on Google Street-View Panorama (GSVP) images to measure the built environment features and human visual walkability perception on commercial streets, revealing how physical features impact public visual walkability perception. Specifically, we collected street images from the Tenjin commercial district in Fukuoka, Japan, using web crawlers. Four walking needs of visual walkability perception—usefulness, safety, comfort, and attractiveness—were measured using the SD method. Meanwhile, using semantic segmentation technology based on deep learning, we identified the proportions of landscape elements in the images, calculating 12 physical features representative of the commercial street environment. Finally, correlation and regression analysis were applied to investigate the influence of the street's physical features on public visual walkability perception. The key questions of this study are as follows: (1) applying an efficient, accurate method to measure visual walkability perception and physical features of commercial streets; (2) analyzing the spatial distribution differences of visual walkability perception in the Tenjin commercial district; (3) exploring the impact mechanisms of physical features on public visual walkability perception, thus providing suggestions for planners to create walkable commercial street environments.

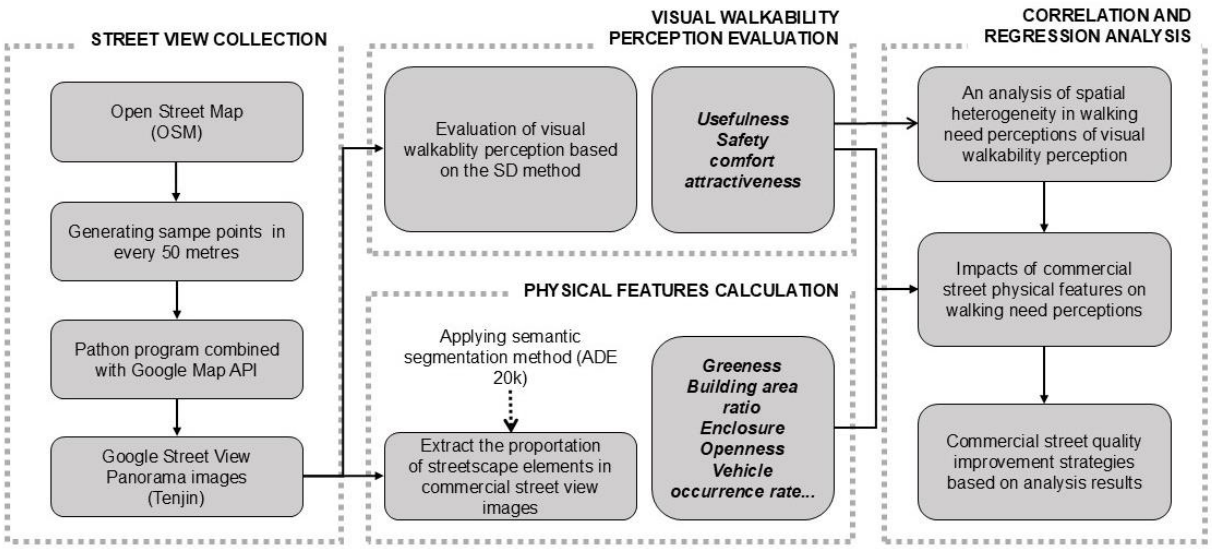


Figure 1. Research framework.

2. Materials and Methods

2.1. Study Area

The research area for this study is the Tenjin area, located in Chuo-ku, Fukuoka City, Japan (Figure 2). The Tenjin area is also a primary commercial center, which is Kyushu. The research area spans approximately 1.8 square kilometers, with average weekday foot traffic ranging from 500,000 to 600,000 people. The Tenjin area is not only the economic center of Fukuoka City but also a significant shopping and entertainment hub in western Japan, attracting a high volume of tourists and residents. The total length of the study streets is approximately 16.2 km, and its road system consists of primary, secondary, and tertiary roads that support pedestrian walking and vehicular traffic, as well as commercial activities. In addition, the Tenjin area contains a number of large department stores, recreational parks, and tourist attractions. The streetscape is varied and rich. As an important commercial area in Kyushu, Japan, the Tenjin area plays an important role in promoting the city's commercial development and showcasing the city's image.

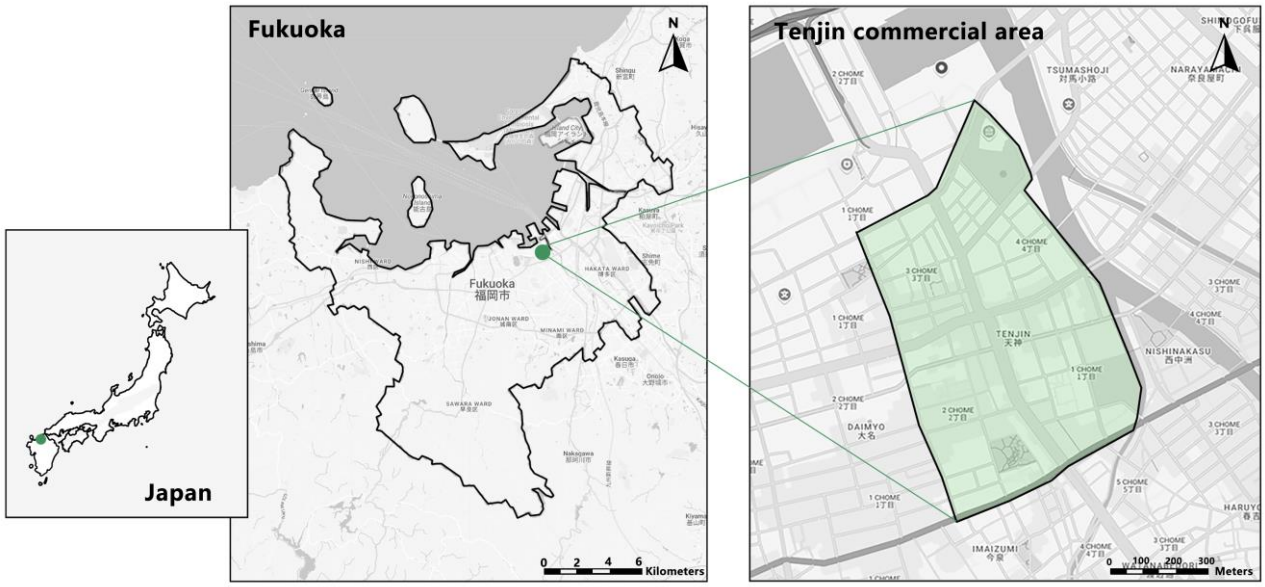


Figure 2. Location of the study area.

2.2. Street-View Image Collection

Street-view images have a wide range of applications in urban research due to their ability to capture real-world scenes in urban environments and provide rich visual data [58,59]. In this study, we obtained the road network data of the Tenjin area in Fukuoka City using Open Street Map (OSM). The study used Arc GIS10.2 to set Google Street-View Panoramic (GSVP) sample collection points every 50 m along the road network and obtained the latitude and longitude information of each sample collection point. A total of 481 sample collection points were generated in the Tenjin area, including 97 on primary roads, 136 on secondary roads, and 248 on tertiary roads. The study collected GSVP images of each sample point by web crawlers that were integrated with the Google Street-View Map Application Programming Interface (Figure 3). The pixels of the GSVP image were set to 2048 × 624, and the pitch angle of the image was set to 0° to achieve a more realistic pedestrian view. To minimize the impact of seasonal variations on greenery in streetscapes, we examined the capture dates of the images to ensure that all streetscape images were taken in April 2023. Additionally, indoor scenes were excluded to maintain consistency. In total, 475 GSVP images were collected for this study.

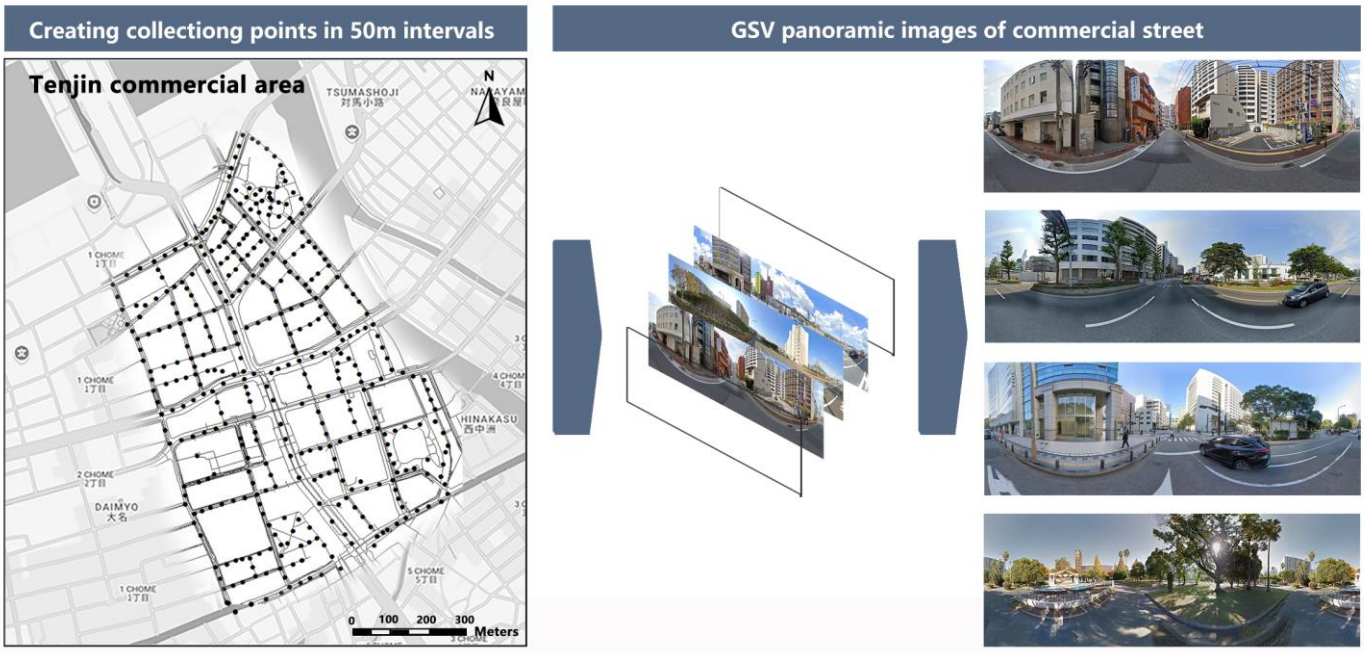


Figure 3. Google Street-View Panorama images collection.

2.3. Visual Walkability Perception Evaluation

In previous studies, Virtual Reality (VR) technology has been used to provide immersive environments, allowing participants to experience motion and other dynamic effects, offering significant advantages in simulating real-world scenarios and improving the accuracy of perceptual assessments [60]. However, VR-based evaluations are characterized by a high level of detail and resource intensity, which often limits the sample size and scalability of such studies. Therefore, in this study, we used the Semantic Difference (SD) method to evaluate the visual walkability perception of GSVPs in the Tenjin commercial district, which includes the four walking-need perceptions (usefulness, safety, comfort, and attractiveness). The Semantic Difference (SD) method was introduced by Charles E. Osgood in 1957 [61] and has been widely used in environmental assessment studies due to its applicability [62,63]. The selection of adjective pairs is particularly important in the evaluation process of the SD method. According to previous studies [32,64], we selected

four walking-need perceptions of usefulness, safety, comfort, and attractiveness as the evaluation indexes (Table 1). The evaluation process of the SD method usually involves 20 to 50 observers. Many studies have shown that students' and the public's perceptions of the environment are highly correlated [65], so students are often used as observers in street environment evaluation [66,67]. In this study, we recruited 35 students (14 graduate students and 21 undergraduate students) as observers to evaluate four walking-need perceptions in 475 samples. Considering the large number of samples to be evaluated in this study (n = 475), the 475 samples were divided into 3 groups and organized into 3 slide presentations (the first slide included 159 images, while the second and third slides each contained 158 images). These slides were projected in a multimedia classroom using an ultra-high-resolution projector to ensure a clear and consistent visual presentation. Before the slide presentations, we provided all observers with an explanation of the definitions for the four walking-need perceptions. Additionally, they were given an overview of all the samples to develop a general understanding of the scoring criteria. During the evaluation process, each street-view image was displayed for 40 s. Observers were instructed to observe the images statically (no interaction was allowed) and evaluate the four walking-need perceptions for each street-view image. To prevent visual fatigue from prolonged observation, a 30-minute break was provided between each group of slides during the evaluation process. The evaluations were based on a five-point scale (1–5), with positive and negative adjectives being compared to the walking-need perception. In this context, higher scores were associated with meanings closer to the adjectives on the right side of the scale. A total of 35 questionnaires were returned. We conducted an intraclass correlation coefficient (ICC) test, and all 35 questionnaires were valid.

Table 1. Characteristics of visual walkability perception.

Evaluated Item	Adjectives in Pair
Usefulness	Useless (1)—Useful (5)
Safety	Unsafe (1)—Safe (5)
Comfort	Uncomfortable (1)—Comfortable (5)
Attractiveness	Unattractive (1)—Attractive (5)

2.4. Street Physical Features Calculation

The semantic segmentation method based on deep learning was used to extract the proportions of streetscape elements from GSVP images and to quantify the physical features of commercial streets in this study. Semantic segmentation, as a computer-vision technique, can classify images at the pixel level (roads, buildings, sky, pedestrians, vehicles, etc.). This method has been widely used in studies for analyzing urban street environments [68–71]. The study employed the semantic segmentation model PSPNet [72] to extract the proportions of streetscape elements from GSVP images. Compared to other semantic segmentation models, such as FCN, SegNet, and DeepLab, PSPNet effectively handles multi-scale objects within scenes and achieves high accuracy, demonstrating superior performance across multiple datasets, including COCO and ADE20K. Additionally, the ADE20K dataset was used as the training dataset. This dataset contains annotations for 150 categories that encompass indoor, outdoor, street, natural landscape, and architectural scenes. This extensive coverage makes ADE20K well-suited for fine-grained segmentation tasks [73]. The PSPNet semantic segmentation model demonstrated advanced performance on the ADE20K dataset, achieving an accuracy exceeding 80%. The collected GSVP images were processed through PSPNet, where the PSPNet decoder categorizes the streetscape elements and calculates the proportions of each element in the GSVP image. As shown in Figure 4, key streetscape elements can be clearly extracted from GSVP images.

Example of semantic segmentation results



The top 15 streetscape elements proportion

Streetscape elements	Mean value	Standard deviation
road	0.318	0.132
building	0.298	0.131
sky	0.175	0.073
sidewalk	0.082	0.105
tree	0.058	0.082
car	0.016	0.026
grass	0.012	0.051
car	0.011	0.022
plant	0.008	0.016
fence	0.005	0.013
wall	0.005	0.014
signboard	0.005	0.008
truck	0.004	0.014
earth	0.003	0.026
pedestrians	0.002	0.003

Figure 4. Example of semantic segmentation and percentage of each tag.

Ewing and Handy (2009) proposed the influential concept of urban design quality, which includes five dimensions: imageability, enclosure, human scale, transparency, and complexity [20]. Subsequent researchers have conducted studies on urban street quality based on these indicators [20,74,75]. Through a review of this literature, we selected 12 physical features that could be counted (Table 2). These physical features have often been used in previous studies to reflect the street built environment [76–80]. Additionally, we incorporated a commercial signage index to reflect the ambiance of commercial streets. Previous studies have highlighted that the atmosphere of commercial streets can significantly influence visitors' willingness to walk and shop, suggesting its potential impact on pedestrian engagement and consumer behavior [81,82].

2.5. Statistical Analysis

In this study, we conducted correlation analysis and regression analysis on the commercial street physical features and visual walkability perception using SPSS 26.0 software. Specifically, the four walking-need perceptions (usefulness, safety, comfort, and attractiveness) were used as dependent variables. The street physical features were used as independent variables in multiple linear regression analyses to explore the specific impact of the built environment on walking-need perception in commercial streets.

Table 2. Commercial street physical features selection and definition.

Physical Feature	Formula	Expression	Definition
Greenness	$G_i = \frac{1}{n}\sum_{i=1}^{n} V1_i\{i \in (1, 2, \cdots, n)\}(1)$	$V1_i$ denotes the proportion of trees, grass, and plant pixels. The sum indicates the total number of vegetation pixels in each image.	It refers to the ratio of trees, plants, and grasses pixels to the overall pixels.
Openness	$O_i = \frac{1}{n}\sum_{i=1}^{n} S1_i\{i \in (1, 2, \cdots, n)\}(2)$	$S1_i$ denotes the proportion of sky pixels. The sum indicates the total number of sky pixels in each image.	It refers to the open degree in the street space.
Enclosure	$E_i = \frac{\frac{1}{n}\sum_{i=1}^{n} V2_i}{\frac{1}{n}\sum_{i=1}^{n} H1_i}\{i \in (1, 2, \cdots, n)\}(3)$	$V2_i$ is the percentage of wall, building, and tree pixels. $H1_i$ is the percentage of road, sidewalk, fence, and earth pixels.	It reflects the degree of enclosure of the street canyon.
Walkable space	$WS_i = \frac{1}{n}\sum_{i=1}^{n} S2_i\{i \in (1, 2, \cdots, n)\}(4)$	$S2_i$ denotes the proportion of sidewalk pixels. The sum indicates the total number of sidewalk pixels in each image.	It refers to the ratio of sidewalk pixels to the overall pixels.
Pedestrian occurrence rate	$POR_i = \frac{1}{n}\sum_{i=1}^{n} P1_i\{i \in (1, 2, \cdots, n)\}(5)$	$P1_i$ denotes the proportion of pedestrian pixels. The sum indicates the total number of pedestrian pixels in each image.	It reflects the proportion of pedestrians appearing in the street space.
Vehicle occurrence rate	$VOR_i = \frac{1}{n}\sum_{i=1}^{n} V3_i\{i \in (1, 2, \cdots, n)\}(6)$	$V3_i$ denotes the proportion of car, bus, and truck pixels. The sum indicates the total number of vehicle pixels in each image.	It refers to the proportion of vehicles appearing in the street space.
Street cleanliness	$SC_i = 1 - \frac{1}{n}\sum_{i=1}^{n} G_i\{i \in (1, 2, \cdots, n)\}(7)$	$G1_i$ denotes the proportion of garbage, scrawl, bits, and bobs pixels, 1—Represents the cleanliness of the street.	It reflects the degree of tidiness in the street space.
Landmark visibility index	$LVI_i = \frac{1}{n}\sum_{i=1}^{n} L1_i\{i \in (1, 2, \cdots, n)\}(8)$	$L1_i$ denotes the proportion of landmark pixels. The sum indicates the total number of landmark pixels in each image.	It reflects the proportion of iconic landscapes or buildings in the overall pixel.

Table 2. *Cont.*

Physical Feature	Formula	Expression	Definition
Transparency index	$TI_i = \frac{1}{n}\sum_{i=1}^{n} GL_i + \frac{1}{n}\sum_{i=1}^{n} WI_i\{i \in (1, 2, \cdots, n)\}$ (9)	GL_i denotes the proportion of glass pixels. WI_i denotes the proportion of window pixels.	It reflects the degree of transparency in the street space.
Commercial signage index	$CSI_i = \frac{1}{n}\sum_{i=1}^{n} S3_i\{i \in (1, 2, \cdots, n)\}$ (10)	$S3_i$ denotes the proportion of commercial sign board pixels. The sum indicates the total number of commercial sign board pixels in each image.	It reflects the proportion of commercial sign board in the overall pixel.
landscape diversity index	$SHDI = -\sum_{i=1}^{n} (P_i * InP_i)$ (11)	In denotes the landscape log, P_i denotes the proportion of the entire community made up of landscape elements i.	It refers to the richness degree of the landscape elements that can be observed in the street.
Environment color diversity	$ECi = 1 - \frac{1}{n}\sum_{i=1}^{n}\left(\frac{P_{ij}}{\sum_{i=1}^{j} P_{ij}}\right)^2$ (12)	P_{ij} denotes the number of j color pixels in i-image, and J indicates the total number of the environment colors in i-image.	It refers to the richness degree of environmental colors that can be observed in the streets.

3. Results

3.1. Visual Walkability Perception Analysis of Tenjin Commercial District

This study explored the current distribution of visual walkability perceptions in the Tenjin commercial district based on four walking-need perceptions: usefulness, safety, comfort, and attractiveness. A comparison of the results for these four walking-need perceptions (Table 3) revealed the following ranking: attractiveness > safety > comfort > usefulness. In the Tenjin commercial district, attractiveness and safety were both high walking-need perceptions. The standard deviation for safety was moderate, indicating a strong sense of safety across the streets with little variation between segments. However, the standard deviation for attractiveness was relatively high (1.089), suggesting an uneven distribution with some sections showing perceptual fluctuations. Usefulness and comfort were medium walking-need perceptions overall, with moderate standard deviations, reflecting clear but stable characteristics across the streets without significant fluctuations.

Table 3. The walking-need perceptions of Tenjin commercial district.

Walking-Need Perception	Mean Value	Standard Deviation	Number
Usefulness	2.931	0.963	475
Safety	3.018	0.922	475
Comfort	2.968	0.985	475
Attractiveness	3.254	1.089	475

By comparing the high and low samples for different walking-need perceptions (Figure 5), the study identified distinct patterns in their manifestation. In the samples with high usefulness, the presence of small-scale landscape elements such as fountains or sculptures enhanced the recognizability and appeal of public spaces, offering places for walking and group activities. Conversely, in the low-usefulness samples, construction barriers and fences diminished the openness of the streets, restricting pedestrian flow. The lack of vegetation made the visual environment monotonous, while the fences obstructed street connectivity, reducing visual permeability and walking comfort.

In the high-safety samples, the street environments were spacious and clean, with designs emphasizing pedestrian-vehicle separation. Clear road zoning effectively reduced conflicts between vehicles and pedestrians. The open street design provided good visibility, allowing pedestrians to easily observe surrounding traffic and the environment. Light-colored streets and buildings were harmonized with the green of natural plants, contributing to a fresh and bright atmosphere. In contrast, low-safety samples had narrow street canyons formed by tall buildings, further restricted by construction areas at some nodes, limiting sky visibility. These spaces with low safety contained obstacles, graffiti, and street litter, causing a cluttered visual experience. The lack of prominent landmarks and relatively monotonous streetscapes diminished the sense of safety.

As shown in Figure 6, in the high-comfort samples, the street trees on both sides of the road were in good condition, providing natural shading. Additionally, high-comfort streets have a large green area and a wide view of the sky above the streets. The sidewalks were spacious and clearly separated from the vehicle lanes. Although the pavement lacked excessive decorations or distinctive landscapes, its design was simple, clean, and orderly, contributing to an orderly street environment. In the low-comfort samples, they exhibit a significant lack of greenery, resulting in an environment devoid of natural elements. The pedestrian streets were narrow and lacked functionality, with some walking spaces even cut off by building corners, preventing pedestrians from walking freely and safely. Low-comfort streets also tended to have dense buildings on both sides, creating a sense of

oppression. Even in areas with slightly open skies, urban infrastructure such as buildings and utility poles fragmented the view, failing to provide sufficient spatial openness. Moreover, the outdated and deteriorated building facades gave pedestrians an impression of poor maintenance and aesthetics.

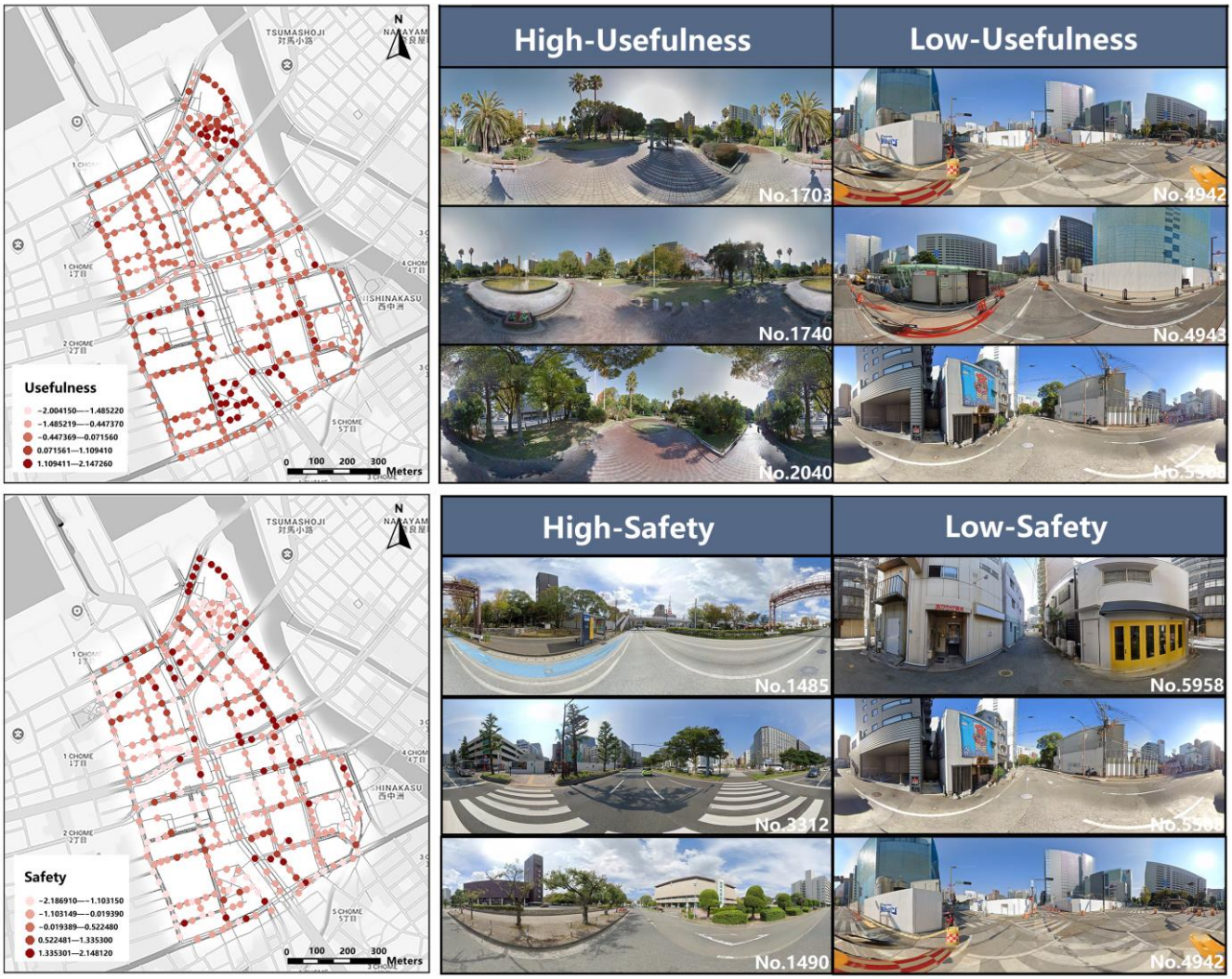


Figure 5. Sample examples of usefulness and safety with high and low values.

Street spaces in high-attractiveness samples had dense and diverse vegetation with vibrant colors. The open streets, combined with a variety of natural landscapes, enhanced the sense of spatiality. The pedestrian paths were wide, flat, and clean. Streets with high attractiveness often featured modern large-scale buildings or unique landmarks, which not only promoted visual appeal but also provided spaces for rest and social interaction. However, in the low-attractiveness samples, the streets lacked greenery and diverse landscape elements, resulting in a cluttered and unappealing environment. The surrounding buildings were tall, and pedestrian paths were obstructed by fences or barriers, restricting walking spaces and negatively impacting the pedestrian experience.

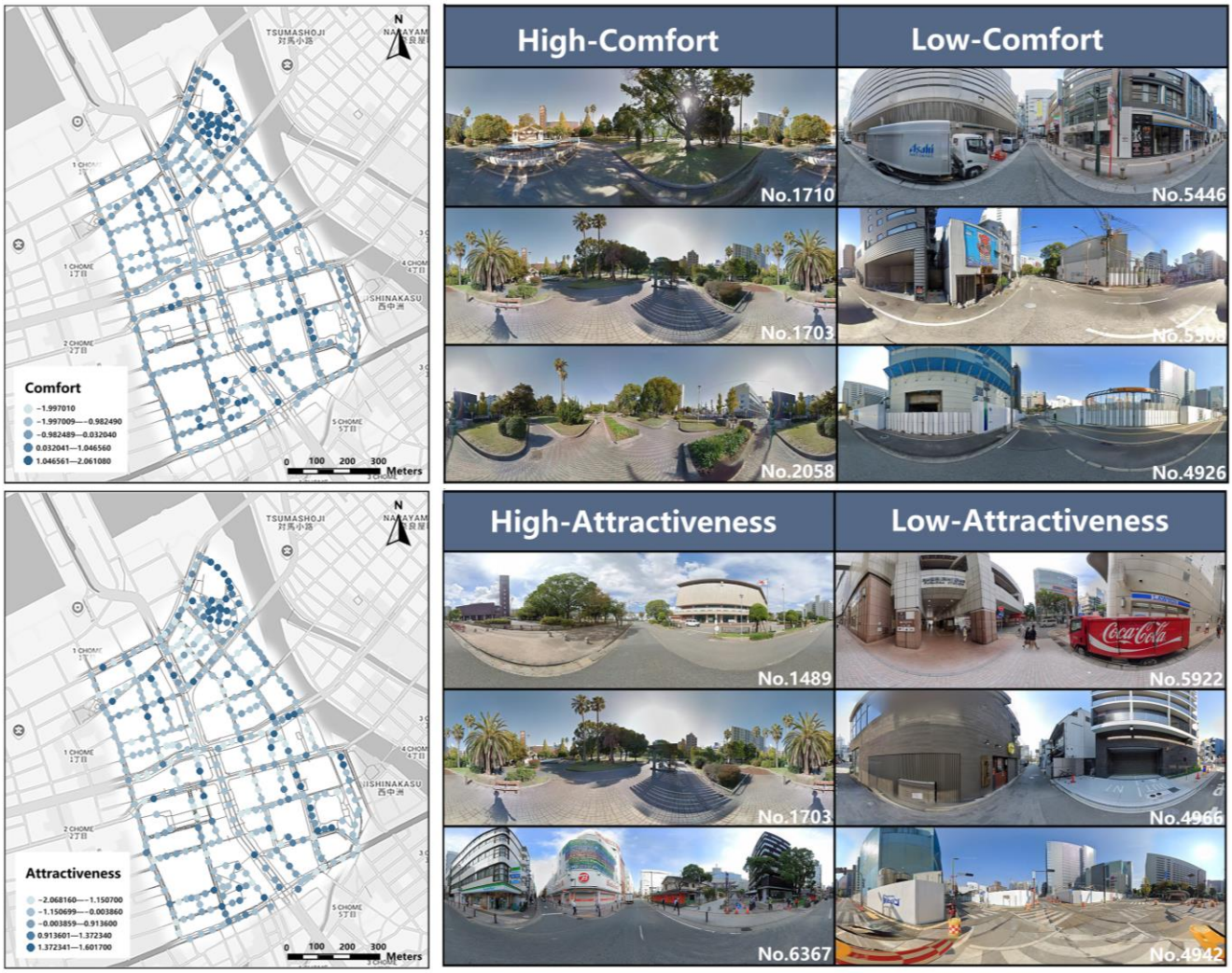


Figure 6. Sample examples of comfort and attractiveness with high and low values.

3.2. Spatial Distribution of Walking-Need Perceptions

To further investigate the spatial distribution of walking-need perceptions, this study analyzed four walking-need perceptions across primary roads, secondary roads, and tertiary roads in the Tenjin commercial district.

As shown in Table 4, primary roads exhibited a high perception of safety and attractiveness, with moderate standard deviations. However, usefulness and comfort were low walking-need perception with smaller standard deviations. This indicated that the perception of safety and attractiveness was particularly prominent on primary roads, whereas their overall usefulness and comfort were relatively low. The design of primary roads in the Tenjin commercial district emphasized safety. These roads were wide with multiple lanes, providing clear and designated spaces for motor vehicles, reducing traffic conflicts and minimizing the risk of accidents. Additionally, primary roads were mostly located on flat terrain, and the wide and simple road design offered unobstructed views, enabling both pedestrians and drivers to navigate easily and effectively. Buildings along primary roads were predominantly high-rise commercial or office structures, characterized by robust construction and orderly arrangement, forming clear street boundaries. The tall and stable walls not only enhanced the sense of boundary but also provided pedestrians with a degree of visual safety, fostering impressions of order and stability. Furthermore, the modern architectural style and uniform appearance of these buildings promoted the visual appeal of the roads. However, as major traffic arteries, primary roads also negatively impacted

pedestrian experiences. The mixed use by pedestrians and vehicles resulted in noise and air pollution, diminishing overall comfort. In addition, the tall and enclosed facades of buildings along these roads lacked transparency in some sections, restricting pedestrian views and hindering navigation for both walkers and cyclists.

Table 4. The result of walking-need perceptions for different roads.

	Primary Road (N = 97)		Secondary Road (N = 136)		Tertiary Road (N = 248)	
	Mean Value	Standard Deviation	Mean Value	Standard Deviation	Mean Value	Standard Deviation
Usefulness	2.727	0.75	3.106	0.953	2.916	1.024
Safety	3.152	1.013	3.022	0.878	2.962	0.902
Comfort	2.845	0.854	3.097	0.945	2.947	1.045
Attractiveness	3.245	0.999	3.378	0.993	3.19	1.165

The secondary roads demonstrated high perception levels across safety, usefulness, comfort, and attractiveness, with standard deviations for all four walking-need perceptions being moderate or low. This suggested that secondary roads provided a balanced and favorable walking experience. As roads that connected various urban areas and served as feeders for traffic distribution, secondary roads generally experienced lower traffic volumes than primary roads, resulting in slower vehicle speeds. This created a safer interaction environment for pedestrians and non-motorized vehicles, reducing accident risks and encouraging activities in these areas. The moderate width of secondary roads, often accompanied by green belts and trees, provided visual buffers that protected pedestrians from external traffic disruptions, fostering a relaxed and secure psychological environment. Spatially, the diverse layout of secondary roads, incorporating green spaces, parks, and commercial zones, offered a variety of activity spaces to meet diverse needs. This diversity also promoted social interactions, enhancing the overall attractiveness and comfort of the area.

In tertiary roads, attractiveness was a prominent walking-need perception, but its high standard deviation indicated an uneven distribution, with some segments lacking appeal. Safety and comfort showed moderate perception levels; however, comfort showed significant variability, reflecting inconsistent distribution. The usefulness was evaluated as a low walking-need perception, indicating poor performance in this aspect. The design of tertiary roads tended towards pedestrian-friendly spaces such as footpaths and parks, with open areas providing gathering and socializing opportunities. These streets often included significant green spaces, parks, and public seating, creating areas for relaxation, leisure, and daily activities while supporting social interactions. Clean roads and well-arranged vegetation reduced visual clutter, offering an enhanced aesthetic experience. However, some segments of tertiary roads suffered from reduced attractiveness. Monotonous building facades lacking visual appeal and the absence of natural elements or greenery in some areas diminished the desire for people to stay. The overall usefulness of tertiary roads was poor, as they were often narrower than primary roads, with limited openness and a lack of well-developed pedestrian infrastructure, restricting walking spaces. Moreover, barriers such as fences, buildings, or construction sites obstructed some routes, further limiting accessibility and convenience for pedestrians.

3.3. Correlation and Regression Analysis

This study conducted a correlation analysis between four walking-need perceptions and 12 physical features using SPSS software, revealing the relationships between different walking-need perceptions and street physical features. The results are shown in Figure 7.

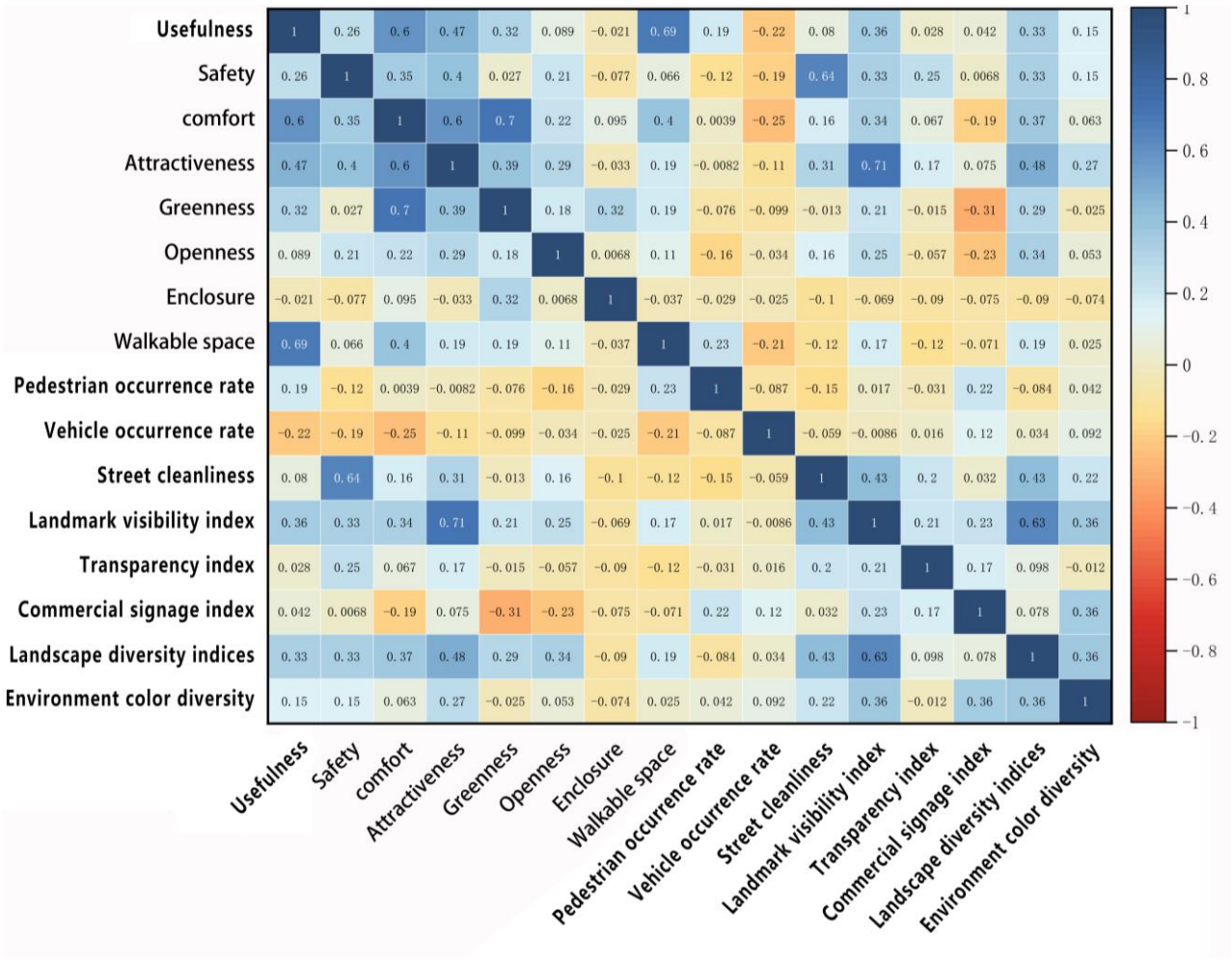


Figure 7. Correlation analysis between walking-need perceptions and physical features.

The correlation analysis for usefulness indicated that usefulness was positively correlated with greenness, walkable space, pedestrian occurrence rate, landmark visibility index, landscape diversity index, and environmental color diversity while negatively correlated with vehicle occurrence rate. For safety, the results showed positive correlations with openness, street cleanliness, landmark visibility index, transparency index, landscape diversity index, and environmental color diversity, and negative correlations with pedestrian occurrence rate and vehicle occurrence rate. Comfort was significantly positively correlated with greenness, openness, walkable space, street cleanliness, landmark visibility index, and landscape diversity index, with a weaker positive correlation with enclosure. However, it was negatively correlated with vehicle occurrence rate and commercial signage index. Attractiveness was positively correlated with greenness, openness, walkable space, street cleanliness, landmark visibility index, transparency index, landscape diversity index, and environmental color diversity and showed a weaker negative correlation with vehicle occurrence rate.

In this study, the street physical features identified through correlation analysis were used as independent variables, while the four walking-need perceptions—usefulness, safety,

comfort, and attractiveness—were treated as dependent variables in stepwise regression analyses. By gradually excluding insignificant physical features, regression models for the four walking-need perceptions were developed.

As shown in Figure 8, the standardized residuals from the regression closely follow a normal distribution, indicating that the residuals meet the assumption of normality. These results provide further support for the validity of the model assumptions.

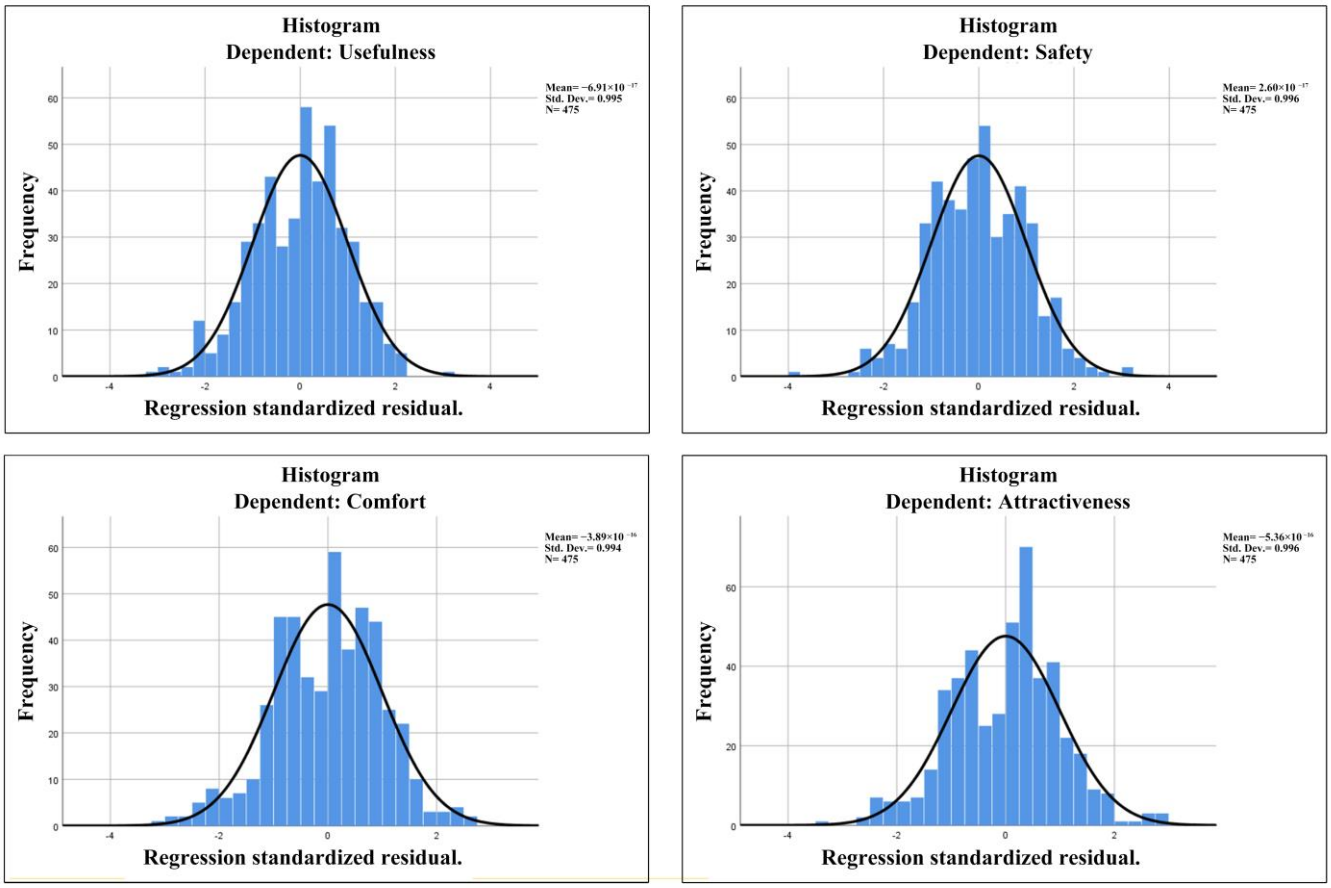


Figure 8. Regression standardized residual of four walking-need perceptions.

As can be seen from Table 5, the regression analysis for usefulness revealed that walkable space, landmark visibility index, and greenness had significant positive effects on usefulness, with walkable space having the most pronounced influence. Environmental color diversity also showed a positive effect (Beta = 0.075), though weaker. In contrast, a higher vehicle occurrence rate was found to decrease usefulness. All variables had low VIF values, indicating no multicollinearity issues. Overall, optimizing walkable space, enhancing landmark landscapes and greenery, and reducing traffic conflicts can effectively improve feasibility perception in waterfront spaces. For safety, the regression results demonstrated that street cleanliness had the most substantial positive impact, followed by transparency index and openness, with Beta values of 0.137 and 0.123, respectively. Conversely, the vehicle occurrence rate negatively affected safety, indicating that reducing traffic conflicts enhances safety perception. All variables had VIF values below 1.1, suggesting no multicollinearity. In summary, improving street cleanliness, increasing street interface transparency, enhancing openness, and alleviating traffic pressure can significantly enhance safety perception. The regression analysis for comfort indicated that greenness had the strongest positive effect on comfort, followed by walkable space and street cleanliness, with Beta values of 0.243 and 0.143, respectively. Conversely, vehicle occurrence rate

and enclosure had negative effects on comfort, while the landmark visibility index had a minor positive effect (Beta = 0.085). All variables showed low VIF values, confirming no multicollinearity. Overall, increasing greenery, improving pedestrian environments, and enhancing street cleanliness are effective strategies to improve comfort in commercial street spaces. For attractiveness, the results showed that the landmark visibility index had the most significant positive impact, followed by greenness and openness, with Beta values of 0.235 and 0.080, respectively. In contrast, vehicle occurrence rate negatively impacted attractiveness, suggesting that reducing vehicle occurrence rate could enhance it. All variables had VIF values below 1.1, indicating no multicollinearity. In conclusion, increasing landmark landscapes and greenery, increasing sky openness, and reducing vehicle flow rate can significantly improve attractiveness.

Table 5. Regression analysis results of Usefulness, Safety, Comfort, and Attractiveness.

	Model	Unstandardized Coefficients		Standardized Coefficients		Sig.	VIF	R^2	F.Sig
		B	Std. Error	Beta	t				
Usefulness	(Constant)	-2.788×10^{-15}	0.030		0.000	1.000		0.561	0
	Walkable space	0.610	0.032	0.610	19.090	0.000	1.102		
	Landmark visibility index	0.191	0.034	0.191	5.644	0.000	1.241		
	Greenness	0.153	0.032	0.153	4.834	0.000	1.088		
	Vehicle occurrence rate	−0.079	0.031	−0.079	−2.518	0.012	1.061		
	Environment color diversity	0.075	0.033	0.075	2.287	0.023	1.177		
Safety	(Constant)	-1.293×10^{-15}	0.034		0.000	1.000		0.457	0.000
	Street cleanliness	0.584	0.035	0.584	16.638	0.000	1.077		
	Vehicle occurrence rate	−0.150	0.034	−0.150	−4.436	0.000	1.005		
	Transparency index	0.137	0.035	0.137	3.957	0.000	1.051		
	Openness	0.123	0.034	0.123	3.565	0.000	1.034		
Comfort	(Constant)	1.455×10^{-15}	0.028		0.000	1.000		0.626	0.000
	Greenness	0.657	0.031	0.657	21.057	0.000	1.232		
	Walkable space	0.243	0.030	0.243	7.980	0.000	1.171		
	Street cleanliness	0.143	0.032	0.143	4.431	0.000	1.319		
	Vehicle occurrence rate	−0.126	0.029	−0.126	−4.328	0.000	1.068		
	Enclosure	−0.090	0.030	−0.090	−2.972	0.003	1.151		
	Landmark visibility index	0.085	0.033	0.085	2.569	0.011	1.380		
Attractiveness	(Constant)	2.177×10^{-16}	0.030		0.000	1.000		0.577	0
	Landmark visibility index	0.642	0.031	0.642	20.499	0.000	1.100		
	Greenness	0.235	0.031	0.235	7.593	0.000	1.07 5		
	Vehicle occurrence rate	−0.080	0.030	−0.080	−2.681	0.008	1.010		
	Openness	0.080	0.031	0.080	2.554	0.011	1.090		

** It is significant at the 0.01 level. * It is significant at the 0.05 level.

4. Discussion

This study aims to investigate the mechanisms by which physical features of commercial streets impact visual walkability perception. Measuring the relationship between them is important for understanding how to optimize walking experiences in urban neighborhoods and improve the quality of public spaces. In this study, GSVP images were automatically collected using Python, and the deep-learning-based semantic segmentation method was applied to analyze street physical features. This approach enabled efficient and precise extraction of various landscape elements in the street-view images, ensuring systematic and consistent data. Meanwhile, the SD method was used to assess four walking-need perceptions of visual walkability perception, and a comprehensive dataset of 475 samples enhanced the representativeness and accuracy of the findings. The combination of these

methods provides a scientific and innovative approach to reveal the relationship between physical features and four walking-need perceptions in commercial streets.

Through the correlation and regression analysis of the physical features and walking-need perceptions in Tenjin commercial streets, this study found that a spacious walking area, abundant street greenery, and the presence of iconic landmarks significantly enhance public walking perception and experience. The study showed that walkable streets positively impact usefulness, supporting prior research on objective walkability and perceptions of walkable streets [68,83]. Wide walkable streets not only provide convenient passage for pedestrians but also encourage more people to walk rather than drive into commercial areas, it is consistent with Southworth's [84] findings on the importance of pedestrian space width for walkability. Additionally, increased vegetation significantly extended residents' walking time; plants enrich the street environment by creating a sense of nature and attractiveness, fostering a more pleasant walking atmosphere [85]. Zhang et al. (2024) indicate that iconic landmarks on streets significantly improve the walking experience for residents by enhancing visual appeal and landmark effects [86]. Moreover, color plays a critical role in shaping uniqueness and identifying features. Studies have shown that distinctive colors and appearances contribute to enhancing spatial memory and emotional connections [87]. Related research indicates that color-rich public spaces can foster an open and inclusive atmosphere, encouraging social interactions among people [88]. The study further validates the positive impact of street cleanliness on safety, consistent with previous research findings [89,90]. A clean environment can reduce anxiety caused by a "sense of disorder". Ghossoub found in a study of New York City streets that disordered elements such as litter and damaged infrastructure significantly decrease pedestrians' sense of safety [91], while a clean street environment enhances their safety perception, making them more willing to use public spaces. The effect of greenness on comfort was found to be the most significant, followed by walkable space and street cleanliness. The study suggests that greenness not only provides shade and reduces temperature but also improves air quality and microclimate, promoting thermal comfort for pedestrians [92–94]. In addition, street vegetation can reduce traffic noise, which can enhance acoustic comfort [95]. This effect makes pedestrians feel more relaxed and pleased in greenery-rich street environments, making walking and staying more comfortable [47]. Wider walkable spaces increase street walkability, making pedestrians pass more comfortably, consistent with the conclusions of Frackelton et al. [96]. On the other hand, a clean and organized walking environment not only improves residents' psychological comfort but also extends their stay, enhancing the walking experience [97]. However, high levels of enclosure will reduce street comfort. High enclosure in street spaces can easily trigger feelings of anxiety and oppression in pedestrians [98,99]. As pointed out by some scholars, open spaces are generally more comfortable for people than enclosed spaces [100]. Additionally, an increased landmark visibility index can significantly enhance street appeal, therefore strengthening place identity. Kevin Lynch, in The Image of the City [101], proposed that landmark landscapes add visual character to streets, helping people recognize specific areas and enhancing distinctiveness. This visual appeal not only strengthens residents' sense of belonging but can also attract tourists and potential investors, promoting neighborhood image and economic value [86]. The positive effects of greenness are also supported by other studies on the benefits of urban greenery for commercial streets [102]. In studies by A.T. Row and J. Jacobs, urban greenery, such as trees and lawns, was shown to significantly improve the urban aesthetic, particularly their visual attractiveness [103]. Finally, the vehicle occurrence rate negatively affects usefulness, safety, comfort, and attractiveness. Streets with high vehicle occurrence rates are more prone to accidents, heightening pedestrians' sense of insecurity. This negative perception of safety also discourages walking, especially among children and elderly individuals [104].

Frequent accidents psychologically increase pedestrian tension, decreasing comfort. Such incidents often lead to street disorder, leaving negative visual elements which in turn reduces the attractiveness of the street.

The analysis of the spatial distribution of walking needs perception in Tenjin's commercial district revealed that primary roads exhibit poor usefulness and comfort, while tertiary roads showed shortcomings in usefulness. To enhance the overall pedestrian environment of urban streets, it is recommended that future street renovations prioritize improvements in usefulness on both primary roads and tertiary roads. Specifically, increasing the number of pedestrian pathways and widening pedestrian spaces can enhance pedestrian flow [105]. Additionally, rational planning of traffic routes effectively facilitates a connection between transit lines, service facilities, and recreational walking paths, thus optimizing the walking experience [106]. Improving the natural environment on primary roads is also a key strategy, which can be achieved by adding more greenery along the streets to boost environmental appeal [107]. For instance, implementing vertical greening along streets [108] not only beautifies the streetscape but also significantly enhances street comfort. To minimize vehicular interference with pedestrian activity, various speed control measures should be implemented into street design, such as shortening intersection distances and reducing turning radii. These modifications can lower vehicle speeds and improve pedestrian safety [109].

This study has several limitations that need to be considered. First, the accuracy of using objective environmental factors to predict perception is typically limited. The study primarily investigates the influence of commercial street environmental features on visual walkability perception from four walking-need perceptions. Second, GSVP images capture only a specific moment in time, which may not comprehensively reflect variations in pedestrian and vehicle appearance rates throughout the day or week. Previous studies have shown that pedestrian and traffic flow exhibit significant temporal variations [110,111]. In future research, we will collect and compare street images from the same locations at multiple time intervals to explore how built environment characteristics influence human activity patterns. Third, this study was conducted in Tenjin, Fukuoka, a central commercial district characterized by its unique geographical location, cultural context, and high-density commercial activities. These factors may differ from those in other commercial areas, and therefore, the findings may not be entirely applicable to all types of commercial districts. Finally, previous research on environmental perception suggests that using students as a substitute for the public is feasible. Our study primarily selected university students as respondents for evaluating walking-need perceptions; however, the users of commercial street environments may include tourists from various cultural backgrounds. This study did not incorporate individual demographic factors such as age, gender, or socioeconomic status into the analysis. Previous research has shown that these socio-demographic characteristics significantly influence perceptions of walking needs. Future research should explore the intersection of socio-demographic factors and walking-need perceptions by integrating these variables into the analytical framework. This approach could provide a more comprehensive understanding of how urban street design impacts diverse population groups and help inform more inclusive urban planning and design practices.

5. Conclusions

In this study, we evaluated the visual walkability perception and quantified the physical features of urban commercial streets based on street-view images using the SD method and deep-learning-based semantic segmentation method. Additionally, correlation and regression analyses were applied to explore the impact of physical features on walking-need perception. The application of these methods to quantitatively assess the objective

environment of commercial streets on a large scale and to capture public walking-need perception with minimal cost is significant for urban planning and environmental design.

The results of the study show that the overall walking-need perceptions of the Tenjin commercial district are ranked as follows: attractiveness > safety > comfort > usefulness. In addition, the results show that there are significant spatial distribution differences in walking-need perceptions in the Tenjin commercial district. Safety perception is more prominent on primary roads, all four walking-need perceptions in the secondary roads at a high level, and the tertiary roads have generally lower scores for all walking-need perceptions. The regression analysis indicates that walkable space and the landmark visibility index have a significant impact on usefulness, street cleanliness emerges as the most influential factor affecting safety, greenness is identified as the primary determinant of comfort, while the landmark visibility index exerts the greatest influence on attractiveness. Based on the differences in the spatial distribution of walking-need perceptions, targeted adjustments and optimization of the physical features of different commercial streets can effectively enhance public visual walkability perception. These strategies can promote residents' health, foster community interaction, and improve overall quality of life. The findings provide practical insights for future urban planning, contributing to the development of pedestrian-friendly urban environments.

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