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Assessing and Comparing the Visual Comfort of Streets across Four Chinese Megacities Using AI-Based Image Analysis and the Perceptive Evaluation Method

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Abstract: Environmental perception studies have long been constrained by research scales due to the difficulties in obtaining users' perceptive data and constructing their relation to environmental attributes. With the help of big data from street view images, this study compares the visual comfort of streets across four Chinese megacities with evidently distinct geographical characteristics. A multi-method approach involving traditional comfort measurements, image analysis based on deep learning algorithms and spatial mapping using geographic information systems was used to investigate the visual components of urban streets at the city scale and their influential mechanisms. In general, the four cities ranked by visual comfort were Beijing first, then Shenzhen, Shanghai and Guangzhou. The results also suggested that the spatial distribution of the four cities' street visual comfort is obviously different. In Shanghai and Beijing, streets with a higher comfort level are mostly concentrated within the central city, while the highly comfort streets are mostly distributed along the coast and rivers in Shenzhen and Guangzhou. Thus, it is reasonable to speculate that the streets' visual comfort relates significantly to their urban planning and construction process. Moreover, seven indicators have been identified as influential to street comfort, among which 'vegetation', 'terrain' and 'rider' are positive indicators, while 'architecture', 'pedestrians', 'motorcycles' and 'bicycles' have negative influences. Comparing street comfort indicators of the four case study cities, it was observed that 'vegetation' and 'terrain' have the most consistent positive influences across cities, while the high visibility of 'building' on streets is most likely to lead to a low level of perceived comfort. The research outcomes provide applicable cues for large-scale street evaluation research and illustrate an efficient street design approach that can both respond to local characteristics and human perceptive needs.

Keywords: visual comfort; street view images; comparative study; spatial distribution; Chinese megacities; semantic segmentation

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1. Introduction

Urban designers are interested in the environmental qualities of places that make them better, not only as settings for physical activity but also as sensorial and social settings [1]. Streets, as one of the most common urban open spaces, have been endowed with increasing importance because of their potential to sustain people's outdoor lives and fulfil their physical, psychological and social needs [2]. With the continuous growth of human needs in public urban spaces, people's perceived sense of comfort has become a vital quality in street evaluation studies. Referring to the existing literature, street comfort can be defined as the physical and psychological satisfaction people obtain when they sensorily interact with street settings [3]. Alfonzo (2005) states street comfort as a critical perceptive need of the public with the potential to create more opportunities for activities [4], increase street vitality and encourage social and consumer behavior [5]. Therefore, designing comfortable streets in urban areas is of great importance since it can promote social interaction, economic development and improve peoples' health and well-being [6].

A better understanding of the relationship between people's perceived comfort and physical street characteristics is necessary for planners and designers to deliver better street environments [7]. However, most studies concerning human perceptions are constrained by research scales due to the difficulties in obtaining users' perceptive data and constructing their relations to environmental attributes. This also leads to a lack of a way to extrapolate large-scale spatial characteristics from small-scale human perceptions, as well as of cross-city and cross-culture perspectives in relevant research arenas. This study proposes that the big data of street view images and image analysis methods based on artificial intelligence (AI) may have the potential to carry out street comfort evaluations at the city scale. Through a multi-method approach involving perceptive comfort measurements, image analysis based on deep learning algorithms and spatial mapping using the geographic information system (GIS), street comfort is measured at a city scale, and the street-comfort-related attributes in different cities are identified and compared. The research outcomes provide cues on how street comfort varies with spatial characteristics within and across cities, and thus, contributes to developing comfortable street design instructions that can be in accordance with local contexts.

1.1. People Perceive Comfort in Streets

It was not until the 19th century that the psychological concept of comfort was first associated with physical environments [8]. Earlier, environmental comfort research mostly focused on the light, temperature, sound and air quality of indoor settings [9], which are indicated by physical attributes, such as temperature, humidity and speed of airflow [10,11]. The concept of environmental comfort was later extended to people's perceived comfort in surrounding environments with the development of human-orientated urban design [12]. In the context of urban streets, people's perceived comfort is normally explored through two perspectives: the subjective users' sensory, emotional, psychological and activity perceptions and the objective indications of comfort perceptions.

Sensory comfort mainly refers to people's satisfaction with environmental attributes in relation to their senses [13]. Existing studies have explored the influences of visual and aural attributes on people's perceived comfort. Among these, the visual aspect is a major theme since it accounts for over 80% of human perception [14]. Visual attributes, such as the degree of unobstructedness, spaciousness, naturalness, the proportion of sky view and openness [15] of streets, have proven to be closely associated. Another important sense that can influence human comfort is sound. Liu and Kang (2018) have proven that there is a strong positive correlation between audio-visual comfort and the street width-to-height ratio [16]. Additionally, the sources of sounds [17,18] and the consistency between functional, visual and aural attributes [19] usually correspond to higher ratings of overall comfort.

Emotional comfort refers to the level of positive emotion that streets can bring people. Previous studies concluded that senses of safety [20], refuge [21], familiarity [22] and privacy [23] are four major aspects associated with human emotional comfort. Among these, the sense of safety is primarily affected by traffic safety and crime rate [24]. Existing evidence has also confirmed that the permeability of street façades, the number of street-side windows and the presence of other people on the street have positive influences on pedestrians' sense of safety [25]. In addition, people may feel more comfortable when they see familiar activities taking place on streets, even if the environment is noisy and crowded [23].

Physiological comfort emphasizes the impacts of the street environment on people's physical health, for example, respiratory comfort and body surface comfort [26]. Respiratory comfort is mostly influenced by air quality, while body surface comfort describes the street's microclimate, that is, the wind, humidity and heat meeting human needs [27]. Additionally, light [28] and sound [29] can also influence people's physiological comfort. There is also some research that explores the effects of streets' spatial structures, especially that of 'street canyon', on street microclimate [9].

Activity comfort measures the perceived state of satisfaction when people use streets for common activities, such as walking, cycling, standing still and socializing [30]. Research on walkable comfort normally explores street environmental attributes that are conducive to walking, such as greenery [31], pavement quality [32] and the availability of street facilities [33]. There are also studies that attempt to disclose which attributes of street settings promote social activities. They find that streets with an appropriate level of social distance [34] and opportunities for staying active [35] normally contribute to higher social comfort.

As a result, a set of indicators related to human comfort were concluded in the investigation on the relation between subjective perceptions and objective environmental characteristics. Quality indicators, such as enclosure, openness and visual depth, are confirmed to be influential to human perceived comfort with 'U' relations [36,37]. These suggest that people may feel most comfortable only when the openness, enclosure and visual depth of streets are within appropriate intervals. Moreover, previous studies have provided abundant evidence that street content indicators such as lawns, flowers, fruit trees [38], sunshades [39] and the design of street-side architecture [5] can promote people's perceived comfort while they walk.

1.2. The Evaluation of Street Comfort

The fundamental reason that planners and designers investigate the relationship between human perception and the surrounding environment is that they aim to modify, maintain and regulate environments so that they not only raise demand but also have physical, social and temporal characteristics that promote positive perceptions [40]. However, this intention has always been impeded by the lack of an established, specific relationship between environmental attributes and human perceptions. The exploration of the mechanisms influencing street comfort developed based on traditional theories and methods in environmental psychology. Using photos and video recordings as visual stimuli, or having participants experience the streets onsite, previous studies have tried to link their sense of comfort to street characteristics with the help of questionnaire, interview and observation methods [41–43]. Later, in a report on pedestrian comfort guidance for London [6], it was argued that street comfort should be continuously investigated within a certain sector. Global Positioning System (GPS) tracking is a commonly used tool in measuring people's perceived comfort level during continuous movement. For example, Duolop et al. (2015) used GPS tracking together with voice and textual recordings to analyze people's continuous but changing experiences while walking [44].

Earlier research on street comfort is mostly carried out on a small scale, normally within a street, a block or a neighborhood [45], since these traditional methods could hardly afford the human and time costs demanded by onsite street surveys conducted at city level. With the development of big data and AI techniques, large-scale measurements of street characteristics that were once hard to quantify have become possible. For example, semantic segmentation has been used to calculate the viewing rate of a street's greenery, sky exposure and color composition [46–48]. The number of people and vehicles [49] on a street can also be identified using object detection to evaluate the street's traffic function [49]. These newly emerged techniques enable the evaluation of street quality at different research scales and provide a basis for visualized spatial analysis together with the help of GIS [50]. It has been 16 years since Google Street View was launched, and the street view images produced have become powerful datasets which have been widely adopted in street design research. The street functions and vitalities can be differentiated by calculating the percentage of elements in street view pictures [51], of which its changing tendency across decades can also be analyzed using its time machine function. There are also studies using street view images to measure pedestrian space index, green view index, light view index and motorization index and explore their influential factors [52]. The application contexts are increasingly broadened and now cover a diverse range of disciplines. For example, models can be built to predict the wind and thermal environment in a wider range based on high-precision data of regional building information and of wind and thermal environments [53]. A recent study identified the intersection point of trees and power lines through semantic segmentation and object detection, so as to benefit the safety management of urban street greening [54]. In addition, there are also studies that using video and images recorded by mobile phones to identify violent behaviors on urban streets and provide technical support for maintaining street safety [55].

The prerequisite of utilizing a massive amount of data, street view images and AI-based analysis methods in street perceptive quality evaluation is meant to establish the connection between human perception and street characteristics. Though attempts have been made [56], they focus more on correlating the presence of people [49] and human activities [51] that can represent vitality to objective environmental characteristics, or on investigating the influences of certain attributes (i.e., green viewing rate [57], openness [58] and enclosure [59]) on human perceptions. There is still a lack of integrated perspective to take environmental attributes, human perceptions and spatial characteristics together into consideration. Furthermore, these connections have not yet been fully developed in city-scale research due to the difficulty of acquiring corresponding human perceptive information. Street characteristics may vary in their geographical, landscape, cultural and developmental attributes, which may also affect the underlying relationship between human perception and street quality accordingly. The fundamental contradiction between individual perception and large-scale environmental evaluation, therefore, not only impedes the development of large-scale perceptive studies, but also of research from a cross-culture perspective.

1.3. The Aim of This Study

This study asserts that exploring perceptions of street quality across cities and developing an understanding of their different effects on human comfort can enrich large-scale environmental perceptive studies and broaden the boundaries of cross-culture research. China is a vast country spanning several latitudes; thus, it has cities with diverse functional, geographical and cultural attributes. Many cultural geography studies have proved the influence of regional differences on spatial morphology [60,61]. Therefore, these differences may also be reflected in the characteristics of urban streets, leading to different design requirements to promote street visual comfort.

Taking four Chinese megacities with evidently different geographical characteristics as examples, this study assesses the visual comfort of urban streets at the city scale based on individual perceptive data collected at the street scale. The differences in street visual comfort within and across cities and the underlying reasons causing these differences are also investigated to improve people's street visual comfort in design practices. With the help of open-sourced street view images, AI-based image analysis techniques, perceptive evaluation and mathematical analysis methods, the following objectives are achieved in this study:

(1) To construct a relation between subjective comfort perceptions and street indicators at the street scale and use it to assess and compare street visual comfort in four Chinese case study cities.
(2) To visualize and analyze the spatial distribution of street visual comfort and of related street indicators and compare within and across cities based on geographical and functional attributes.
(3) To develop design instructions to enhance street visual comfort for the four cities.

2. Materials and Methods

In response to the above objectives, this study first used semantic segmentation to calculate the percentage of each street indicator in the big data of city street view images. Streets were then clustered based on the percentage attributes of their indicators. The representative streets of each type were selected for visual comfort evaluation using an online questionnaire-based survey. Through correlational analysis, the connection between the percentage of street indicators and people's perceived visual comfort was established and then used to construct a model to predict street visual comfort for the whole city. The spatial distribution of street comfort and its influential indicators were also visualized using kernel density analysis and the GIS platform. The whole process was conducted on four Chinese megacities, Beijing, Shanghai, Shenzhen and Guangzhou, the results of which were compared and analyzed together with their urban planning and functional characteristics.

2.1. Study Sites

This study selected four Chinese megacities, Beijing, Shanghai, Guangzhou and Shenzhen, as case study sites to assess and compare street visual comfort based on the following criteria:

First, they are the top four most developed cities in mainland China [62], of whom the urban development process has already progressed into a mature stage. Now, higher requirements have been put forward in the selected four cities to improve urban livability. In addition, they have distinctive characteristics in geographical locations, spatial forms, functions and city development positions. Beijing is in the north of China, and Shanghai is located in the eastern coastal area, while Shenzhen and Guangzhou are representative cities in the south. As for spatial form, Beijing and Guangzhou stick to centralized development, Shanghai belongs to the radial development type, and Shenzhen is a typical linear city. With respect to city functions and development positions, Beijing is the capital city of China and, hence, also carries the function of being its political center. Shanghai is the well-known national economic center, which also has the function of international cultural communications. Shenzhen and Guangzhou are among the first cities that opened up along the southern coast, which has led to a strong atmosphere of innovation and entrepreneurship.

The higher requirements for urban development and the huge differences between the cities and their street characteristics make them appropriate case study cities for investigating street comfort and comparing across cities. The study has chosen the Fourth Ring Road (671 km^2) of Beijing and the Outer Ring Road of Shanghai (665 km^2) as research boundaries, while the city of Shenzhen takes the south area of the Ring Road (1339 km^2), and Guangzhou takes the area between the Ring Road and the Guangzhou-Foshan-Jiangmen-Zhuhai Expressway (1075 km^2) as its study site, as seen in Figure 1.

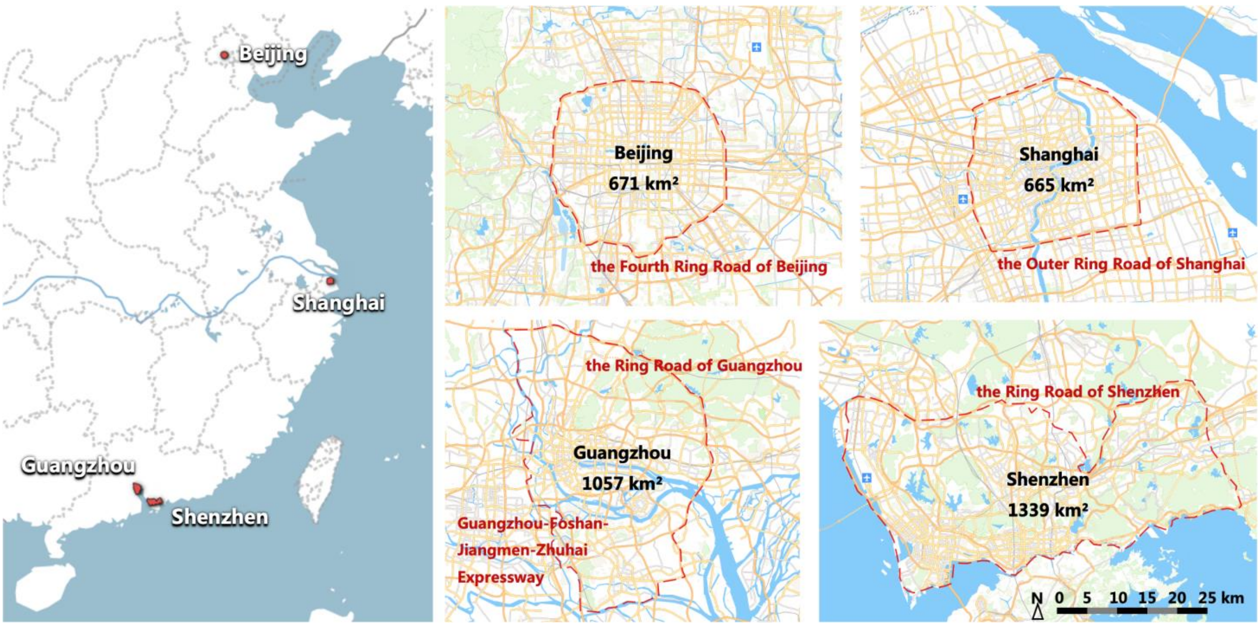

Figure 1. The research scope of each case study city.

2.2. Data Sources

The street view image data used in this study were obtained in 2019 from the Baidu open-sourced map application program interface through Python programming software. The Baidu street view dataset contains relatively comprehensive urban street view data for Chinese cities with an update period of around three to six months for megacities. The street view image data of each spot contain both the street image and its coordinates. All street images take the acute angle of the front direction, and the pixel of each image is 478 × 444 dpi. In total, there are about 819,000 street view images in Beijing, 609,000 in Shanghai, 958,000 in Guangzhou and 906,000 in Shenzhen within the designated research areas.

2.3. Street Classification Based on the Percentages of Street Indicators

The categorization of urban street view images included two main steps: the calculation of the percentage of street indicators and the cluster analysis to categorize them (Figure 2). First, the street indicator label was assigned to each pixel of the street view image based on the 19 categories of street indicators in the street view image tag library provided by the Cityscape website, which contained 'road, sidewalk, building, wall, fence, pole, traffic light, traffic sign, vegetation, terrain, sky, person, rider, car, truck, bus, train, motorcycle and bicycle'. The proportion of street indicators in each street image was then calculated using DeepLab V3^{+} semantic segmentation technology [63], namely, the visibility of street indicators. The visibility of street indicators was used as the variable in the cluster analysis to classify streets according to their characteristics. Hierarchical cluster analysis was then conducted to merge types with high similarities.

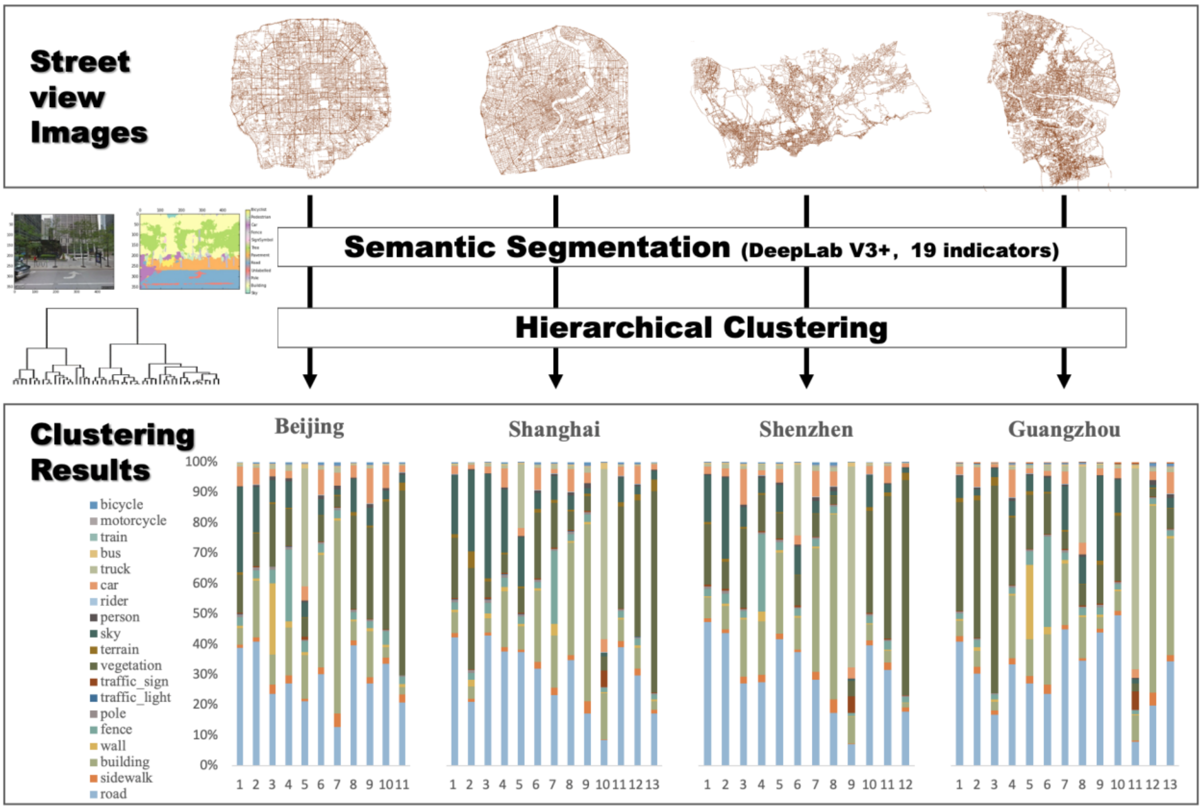

Figure 2. Street classification results of four case study cities.

The final classification results showed that there are 11 typical street types in Beijing, 13 types in Shanghai and 12 types each for Guangzhou and Shenzhen. Though slight differences exist, 'bicycle', 'vegetation', 'building' and 'sky' are the major street compositions in all the four cities that take account of over 60% of street images in total. In addition, every city has three types of streets with 'vegetation' as the main characteristic, two types of streets dominated by 'building' and one type dominated by 'truck'.

2.4. Street Comfort Evaluation Using a Questionnaire-Based Online Survey

Street images were randomly selected from each type as visual stimuli for comfort evaluation. People's perceived comfort from each selected street image was evaluated through an online questionnaire, which was designed and edited using the Tencent online questionnaire website. A total of four sets of formal questionnaires and four sets of verification questionnaires were issued. Each set of questionnaires contained one sample picture for each of the street types in a city.

Participants were recruited online through the WeChat platform, respectively, in the four targeted cities and were also randomly assigned with questionnaires. They were asked to rate each street image with a five-level Likert scale, [64] in which 1 represented 'very uncomfortable', and 5 meant 'very comfortable'. Cross-validation is realized by comparing the mean values of street comfort rated in the formal questionnaire sets with those obtained from the verification sets of each city. The results show that, in general, no difference exists, and therefore, the sampling results are regarded as representative.

A total of 334 valid responses about Beijing streets were obtained, with a male–female participant ratio of 1:1.38 and an average age of 25 (SD = 9.08). For Shanghai streets, 334 valid responses were also obtained, and the ratio of male to female participants was about 1:1.42 with an average age of 25 (SD = 7.80). Three hundred and thirty-two evaluation results were collected for Shenzhen streets, with a male-to-female ratio of 1.83:1 and an average age of 22 (SD = 6.72), while a total of 335 valid samples of street comfort ratings were collected for Guangzhou, with a male-to-female ratio of 1.46:1 and an average age of 23 (SD = 7.08).

2.5. Data Analysis

2.5.1. Calculating the Overall Street Comfort Level of the Four Case Study Cities

The overall street comfort level of each city was calculated using the weighted calculation of the street comfort rating for each street, which can be defined as:

$$C = \sum_{i=1}^{n} (Ci \times Mi) \div Msum \quad (1)$$

where
C: the average street comfort level of a city;
n: the number of street types of a city;
i: the type i city street;
Ci: the comfort level of the type i street;
Mi: the number of type i street spots in a city;
$Msum$: the total number of street spots in a city.

2.5.2. Relating People's Perceived Comfort with Street Characteristics

Correlational analysis was used to establish the connection between street indicators and visual comfort. The p-value of significance test and the coefficient R of the Pearson correlational analysis revealed the degree of influence street indicators have on people's perceived visual comfort. The influential mechanism between street indicators and people's perceived visual comfort can also be implied by the positive and negative effects of each relevant street indicator.

2.5.3. Visualizing and Comparing Street Comfort within and across Cities

To compare the influential mechanism of street comfort and visualize the distribution characteristics of street comfort across cities, the study graded the visibility of street comfort indicators and their comfort value into the high, medium and low levels according to their thresholds. Further, kernel density analysis was conducted on street spots with high levels of positively and negatively related street comfort indicators, as well as on those with high and low levels of visual comfort ratings. The comparison across cities on the distribution characteristics of street comfort indicators and street comfort level was then visually presented using GIS and discussed with considerations of city spatial and functional characteristics.

3. Results

3.1. Manipulation Checks

Questionnaire responses were analyzed using SPSS V26 and were examined for internal consistency with Cronbach's α. It is the preferred measure of inter-rater reliability when cases are rated in terms of an interval variable or interval-like variable [65]. The α values of the street comfort evaluation results showed sufficient internal consistency (Cronbach's α (Beijing) = 0.769; Cronbach's α (Shanghai) = 0.858; Cronbach's α (Shenzhen) = 0.851; Cronbach's α (Guangzhou) = 0.887; α > 0.7) and thus proved to be reliable for further analysis.

3.2. Street Indicators Relating to Street Comfort

In general, seven street indicators are identified as being influential to city street comfort, among which 'vegetation', 'terrain' and 'rider' have positive influences, while 'building', 'pedestrians', 'motorcycles' and 'bicycles' prove to have negative effects. Comparing street comfort indicators of the four case study cities, it can be observed that vegetation and terrain have the most consistent positive effects across cities, while the high visibility of 'building' in streets is most likely to lead to a low level of perceived comfort. Additionally, the compositions of comfort and influential street indicators in Guangzhou and Shenzhen are very similar, both with more negative street indicators than positive ones. Beijing and Shanghai are distinctive from each other and from the other two cities. Three street indicators, 'vegetation', 'terrain' and 'rider' were proven to be in relation to visual comfort in Beijing and all have positive effects. 'Vegetation' and 'building' are related with visual comfort in Shanghai with oppositive effects, as seen in Table 1.

Table 1. Street indicators with influences on street comfort in four case study cities.

	Beijing	Shanghai	Shenzhen	Guangzhou
Positive effects	Vegetation Terrain Rider	Vegetation	Vegetation Terrain	Terrain
Negative effects	/	Building	Building Person Motorcycle Bicycle	Building Person Motorcycle Bicycle

The correlational analysis results of Beijing streets found that three street indicators, 'rider' (R = 0.640, $p < 0.05$), 'terrain' (R = 0.629, $p < 0.05$) and 'vegetation' (R = 0.769, $p < 0.01$), can promote people's perceived visual comfort. The results of kernel density analysis showed that streets with high visibility of 'rider' were mainly distributed around Sun Palace Park and Longtan Lake block, while streets with high visibility of 'terrain' were distributed around several urban ecological parks, including Laoshan Park, Tianyuan Park and Olympic Park. Around the north side of the university district and Taikoo Li Sanlitun, as well as the south side of the Taoyuan Li community, there are lots of streets with high visibility of 'vegetation', as seen in Figure 3.

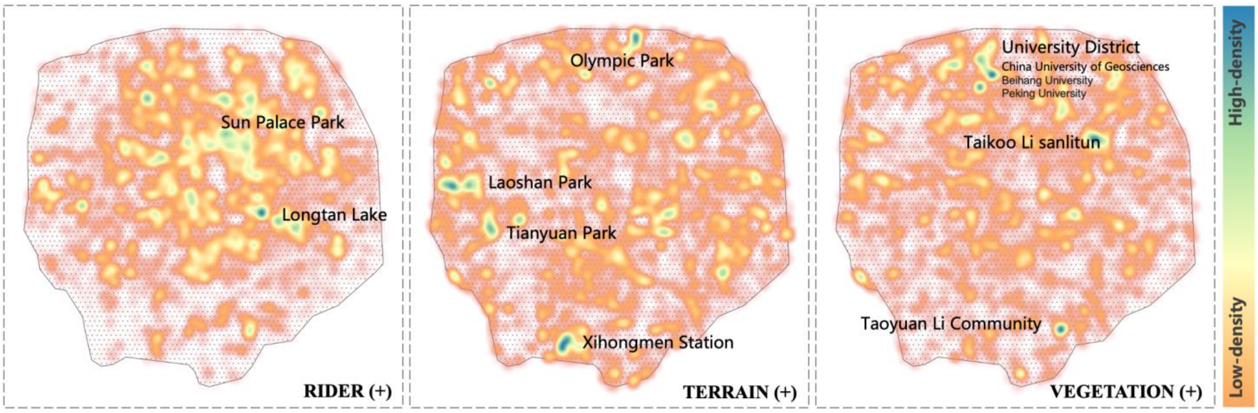

Figure 3. The distribution of high-visibility street indicators with positive effects on street comfort in Beijing.

The Shanghai results revealed that only 'building' ($R = -0.579$, $p < 0.05$) and 'vegetation' ($R = 0.782$, $p < 0.01$) are related to street comfort, with 'vegetation' having a positive influence, while 'building' can inhibit people from obtaining visual comfort from these streets. Streets with high visibility of 'building' are gathered around Yu Garden and Shanghai Railway Station, which is also the old city centre of Shanghai. As for the streets with high visibility of the positive indicator 'vegetation', no evident clusters have been observed. Such streets are mostly scattered throughout the city but more prevalent in the north of the city, for example, around Gangcheng Garden, the Wujiaochang Sub-District and Shanghai University, as seen in Figure 4.

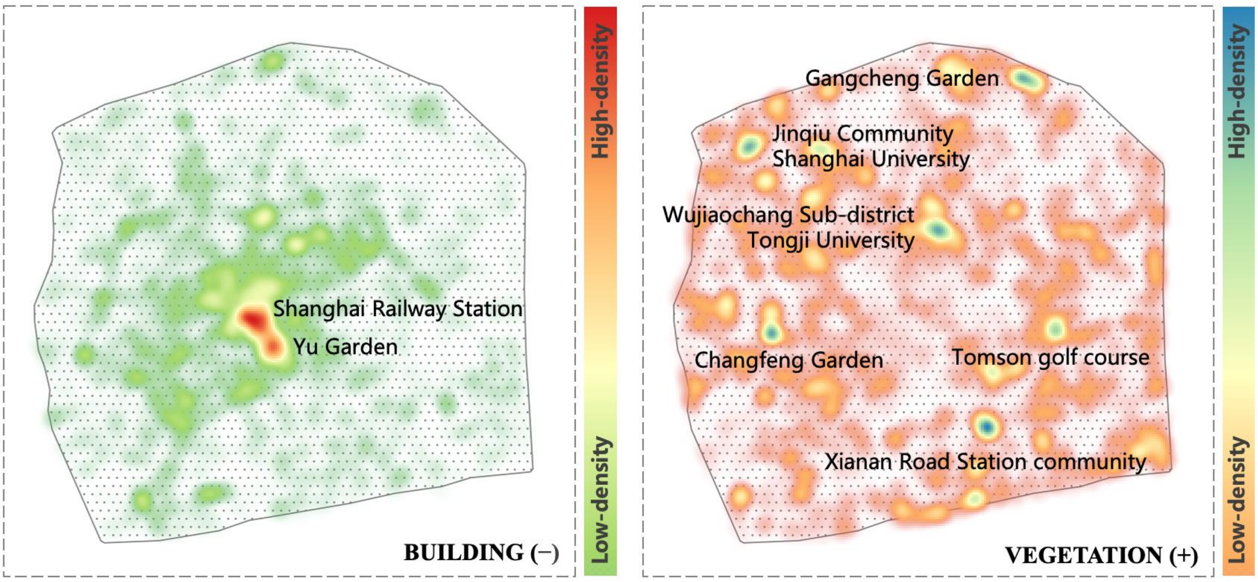

Figure 4. The distribution of high-visibility street indicators with positive effects on street comfort in Shanghai.

The correlational analysis results of Shenzhen streets showed that there are two positive indicators, 'vegetation' ($R = 0.723$, $p < 0.01$) and 'terrain' ($R = 0.748$, $p < 0.01$), and four negative indicators, 'building' ($R = 0.705$, $p < 0.05$), 'pedestrian' ($R = 0.658$, $p < 0.05$), 'motorcycle' ($R = 0.627$, $p < 0.05$) and 'bicycle' ($R = 0.594$, $p < 0.05$), relating to street visual comfort. Analysis results also illustrate high visibility of positive indicators that are mainly distributed in the south of the city, including the port of Shenzhen Bay, the Science and Technology Park and the Botanical Garden. Streets with high visibility of negative indicators are mainly concentrated in the central and northern areas, such as Jiahe Garden, the Tongsheng

Industrial District and the Shangmeilin community, as well as Luohu Station in the southern coastal area, as seen in Figure 5.

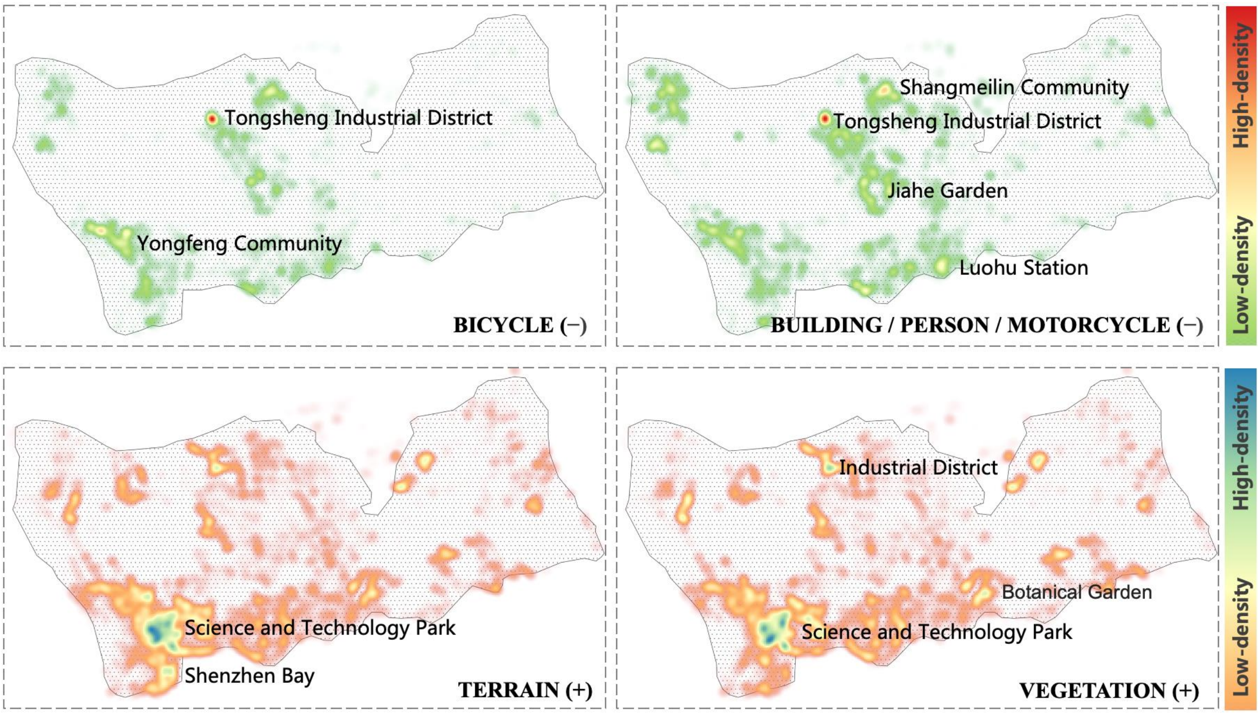

Figure 5. The distribution of high-visibility street indicators with positive and negative effects on street comfort in Shenzhen.

The results of Guangzhou show that only 'terrain' (R = 0.579, $p < 0.05$) promotes street comfort, while four indicators, 'building' (R = 0.695, $p < 0.01$), 'pedestrian' (R = 0.833, $p < 0.01$), 'motorcycle' (R = 0.723, $p < 0.01$) and 'bicycle' (R = 0.732, $p < 0.01$), have confirmed inhibitive effects. The results of kernel density analysis show that the streets with high visibility of 'terrain' were gathered around the Guangzhou Science Town, Changzhou Island and Dishuiyan Forest Park, while the four negative indicators of 'bicycle', 'motorcycle', 'building' and 'pedestrian' were mainly distributed on the streets of the Guangyuan West overpass, Jinan University, Sun Yat-sen University and Xinghai Garden, as seen in Figure 6.

3.3. Comparing Street Comfort Distribution within and across Cities

The average comfort level of Beijing streets was rated the highest (3.51) among the four case study cities. Among them, the highly comfortable street spots accounted for about 63% of the total number, and the rest of the street spots were almost all calculated to have a low level of comfort. The visual street comfort distribution shows that the highly comfortable streets mainly surround the Ring Road, with several evident clusters in the northeast and the west of Beijing. Zhongguancun is the major area with low visually comfortable streets, as seen in Figure 7.

The mean value of the overall comfort level of Shanghai streets was 3.34, ranking third in the four case study cities. Thirty-one per cent of the street spots were calculated as highly visually comfortable, while only 16% of the total provided people with a very limited sense of comfort. Over half of the street spots were rated a medium level of visual comfort. In Shanghai, the highly comfortable streets reveal a polycentric distribution; that is, there is at least one cluster area of these streets within each administrative region. Furthermore, the low visually comfortable streets are also distributed along the main road, especially along the Inner Ring Road and the main road across the Wujiaochang area, as seen in Figure 8.

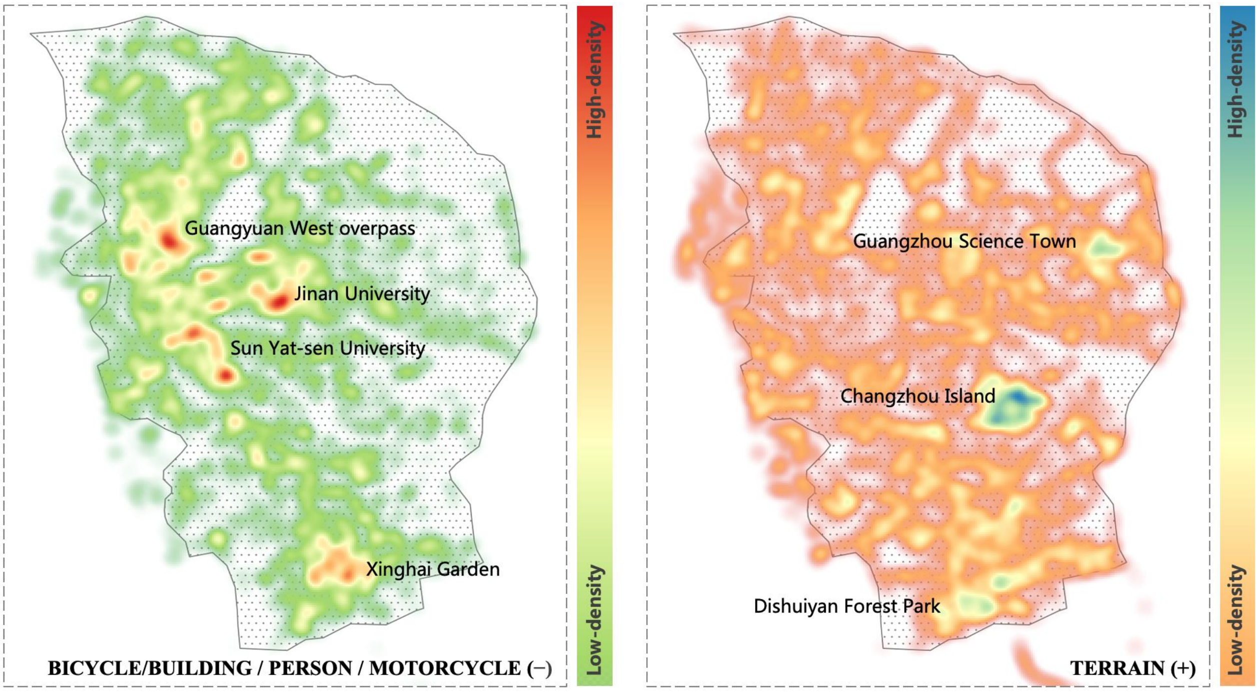

Figure 6. The distribution of high-visibility street indicators with positive effects on street comfort in Guangzhou.

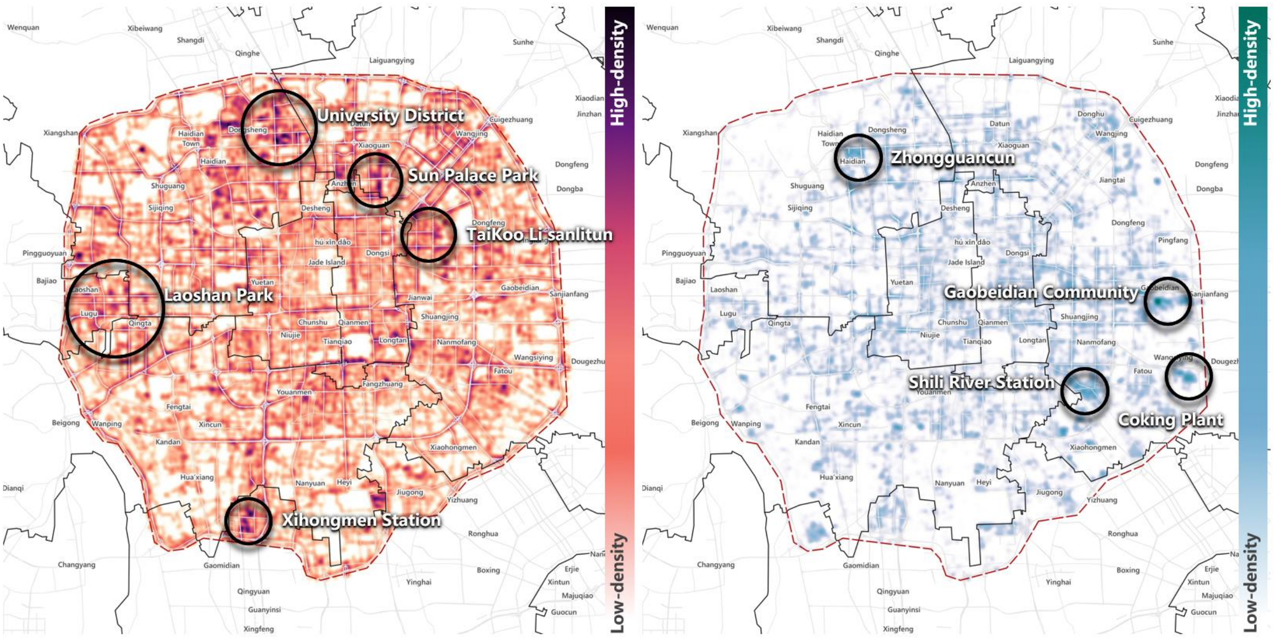

Figure 7. The distribution of street comfort level in Beijing.

The mean value of the overall comfort level of Shenzhen streets was 3.41, ranking second among the four cities. Among them, the highly comfortable street spots accounted for about 25% of the total streets, and 19% of streets belonged to the low comfort level. High visual street comfort is mainly observed in the coastal areas, such as Shenzhen Bay, while the distribution of streets with a low level of visual comfort is mainly concentrated within the city center, as seen in Figure 9.

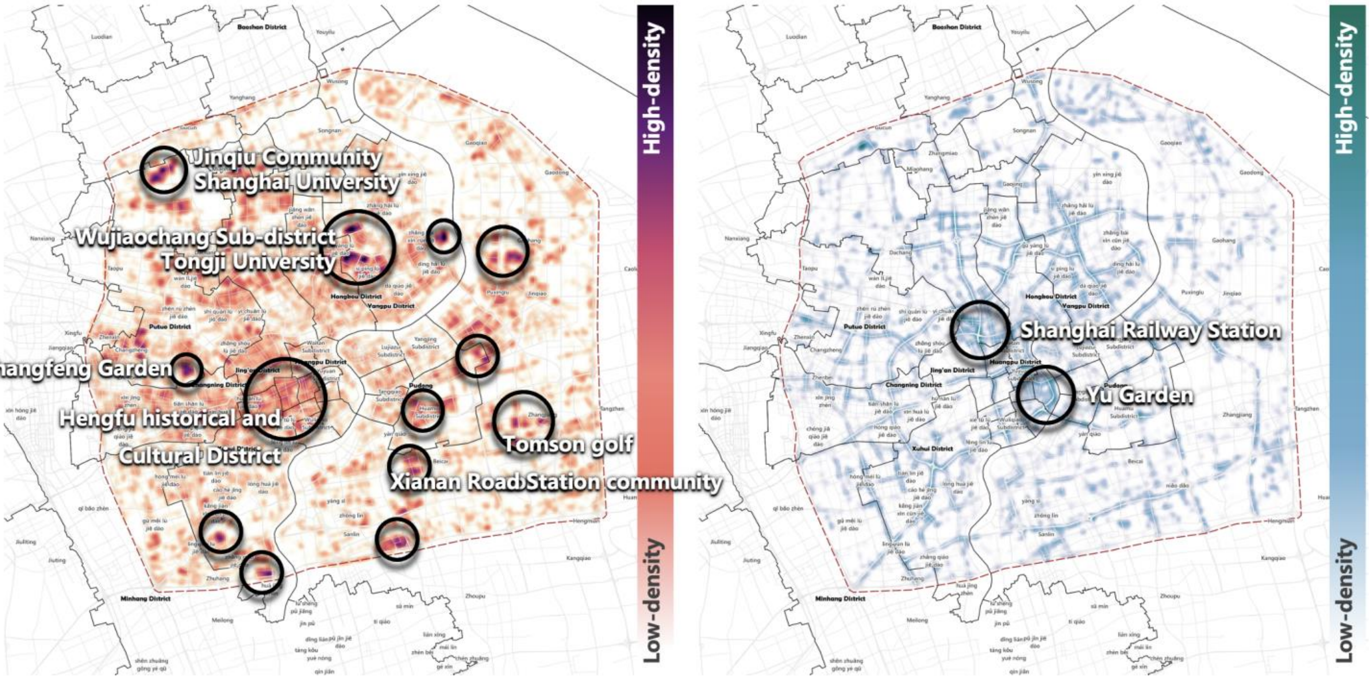

Figure 8. The distribution of street comfort level in Shanghai.

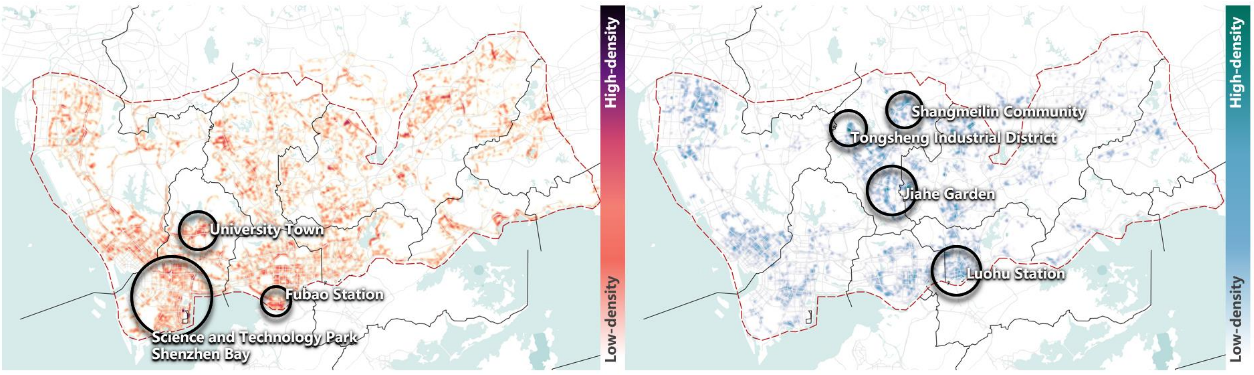

Figure 9. The distribution of street comfort level in Shenzhen.

The average comfort level of Guangzhou streets was rated the lowest (3.25) among the four case study cities. The highly comfortable street spots accounted for 17% of the total and the low-level spots for 36%. Results also suggest that streets with a high level of visual comfort are scattered throughout the city, with several clusters around Guangzhou Science Town, Dishuiyan Forest Park, Changzhou Island and Tianhe Park. Streets with a lower level of visual comfort were observed to be evenly distributed inside the study area; no evident aggregations appeared, as seen in Figure 10.

The ranking of the mean visual street comfort of the four case study cities is generally in accordance with the percentage of street spots with high comfort levels in each city. In terms of the street comfort distribution, the characteristics of the high-level streets in Beijing, Shenzhen and Guangzhou are basically in line with their positive indicators' distribution characteristics. However, no evident overlap has been observed between the highly comfortable streets and the positively related vegetation indicator in Shanghai. The aggregations of the low-level streets in Shanghai and Shenzhen are basically consistent with the distribution characteristics of their negative indicators, but this consistency does not appear in Beijing or Guangzhou.

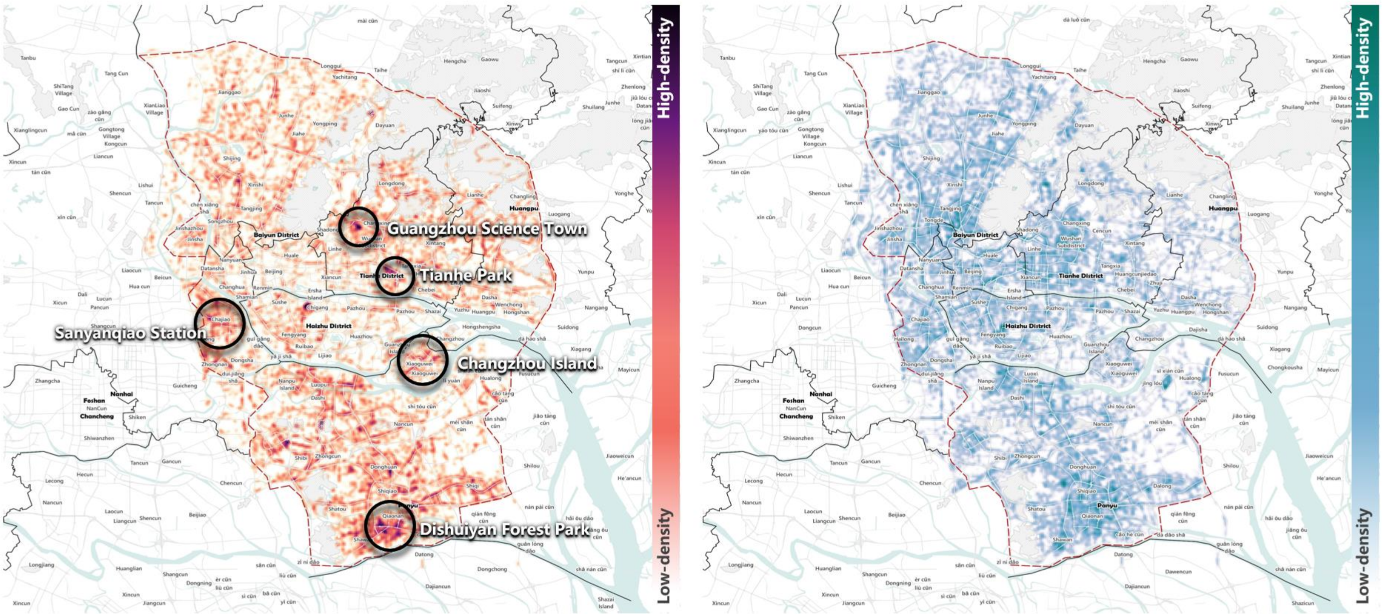

Figure 10. The distribution of street comfort level in Guangzhou.

4. Discussion

Setting out from a typological perspective, this study managed to assess street comfort at the city scale according to human comfort perception collected at the street level with the help of street view big data, deep learning algorithms and kernel density analysis. Through classifying city streets based on their indicator compositions, evaluating people's perceived comfort in each street type and correlating perceptive ratings with street indicator characteristics, street comfort, its related indicators and its influencing mechanisms within and across four megacities in China, Beijing, Shanghai, Guangzhou and Shenzhen are compared.

4.1. Streets Comfort Distribution Is Highly Influenced by Urban Planning Process

Research findings suggest that the spatial distribution of street visual comfort in the four cities is obviously different but related to their urban planning and construction processes. For example, the highly visually comfortable streets in Beijing are mainly distributed along the skeleton road network, which is basically consistent with the structure of the road network left by various dynasties throughout Beijing's history [66]. They emphasize Beijing's old city area, a political and cultural center of China. However, in Shanghai, people perceive less street comfort in the old city area, which is also in line with its planning intention of developing a multicenter city mode [67]. Additionally, street spaces in the old city area are insufficient and often need to balance between traffic and aesthetic functions, thus leading to a relatively lower level of street comfort compared with newly constructed districts. Though not specifically about visual comfort, similar findings were found in a study conducted in certain districts of Nanjing, suggesting that the spatial comfort of roads is evidently lower in a historical urban area [56]. As for two cities in the Pearl River Delta, the grid development pattern of Shenzhen has enlarged the scope of the city center. This is evident in the scattered distribution of its highly comfortable streets. In addition, due to the inherent advantages of coastal development and urban strategy [68,69], there is also an obvious aggregation of highly comfortable streets in Shenzhen's coastal areas. The consistency between the distribution of street comfort and the characteristics of Guangzhou city is reflected by the low level of visually comfortable streets. It can be observed that low-comfort streets are scattered throughout the city partly due to its evenly distributed urban villages. Moreover, the boundary between commercial and residential areas of the city is blurred because of the living pattern shaped by the large number of migrant workers in Guangzhou [70], perhaps leading to the low quality of streets in almost all the city's districts. In general, the streets with a low level of comfort are mainly concentrated in the old city center and urban peripheral area. Therefore, the improvement in street comfort level needs to be implemented in accordance with the city development and urban regeneration process.

4.2. Design Implications Based on Comfort-Related Street Indicators and City Characteristics

Among street indicators identified as influential to human comfort, only the positive effect of 'vegetation' has been widely confirmed in previous studies, with very little direct evidence of the others. This is possibly because the indicators identified from street view images are not expressed in the same way as the indicators investigated by previous studies. For example, the negative indicator of 'building' in this study mainly refers to the visual discomfort caused by the cramped spatial layout of street-side buildings according to the principle of street image analysis. In previous studies, it was found that the aesthetics, color and interface permeability of building façades [71,72] can improve street comfort under the same pattern of spatial building layout. Research attention has also been paid to the relationship between the texture and form of building façade and human visual evaluations [73]. In addition, the use of 'terrain' is an important design approach to enhance spatial interest [74], which may explain its positive influence on street comfort in this study. The positive effect of 'rider' on street visual comfort in Beijing may be explained by the large spatial scale of Beijing streets; the moving cyclists can bring vitality to street life. The presence of pedestrians, motorcycles and cyclists may reduce coherence and thus weaken the sense of comfort [75] when the spatial scale of urban streets is relatively small, such as in Guangzhou and Shenzhen. As for the different observed influences on street comfort and the distribution of indicators in relation to street comfort, these may depend more on the characteristics of the city itself and its most significant development concerns. For example, streets with a high visibility of 'vegetation' are mainly distributed around the schools and commercial and residential areas in Beijing and Shanghai, while in Shenzhen, they are largely gathered around the science and technology park and urban green spaces. These differences generally appeared consistent among the urban development differences among the three cities.

Taking both the distributions of street visual comfort in cities and of the comfort-related street indicators into consideration, design implications for the four case study cities can be concluded accordingly. For the areas aggregated with a low comfort level of streets in Beijing, the existence of 'vegetation' and 'terrain' is extremely insufficient. Thus, increased street vegetation and the use of terrain on the Second Ring Road in Beijing may be helpful. In terms of Shanghai, city areas with the greatest number of low-comfort streets are accompanied with the most amount of 'buildings' with a negative effect, and the least 'vegetation' with a positive influence on street comfort. Increasing street vegetation and strictly controlling building density along Huangpu River in Shanghai can enhance its street comfort in the old city area. The distribution of low-comfort streets in Shenzhen is totally in line with the distribution of its negative indicators of 'building', 'person' and 'motorcycle'. Because the 'person' and 'motorcycle' can hardly be regulated through design, it is assumed that increased street vegetation and the use of terrain along the coastal area and in the middle of Shenzhen city can benefit the general comfort level of Shenzhen streets. In addition, regulation of pedestrian, motorcycle and cyclist traffic and control of building density at its center can also be helpful. The regulation of pedestrian, motorcycle and cyclist traffic is also important in Guangzhou, especially in streets in its western districts. In general, this study evaluates street visual comfort and investigates its influential mechanism at a city level, and thus implies an approach for carrying out environmental perception research that can connect to planning perspectives.

4.3. Limitation

Though the study objectives were all achieved, and the research outcomes generally appeared to be reasonable, some limitations still exist in this study. First, the study used computer semantic segmentation to identify and calculate the indicators in the street view images. Limited by the accuracy that the deep learning algorithm can achieve, there may be a difference between the analysis results with the indicator composition of the real street view. Moreover, street comfort evaluation was conducted online using street images as visual stimuli, which may also lead to deviations compared with using real settings as rating stimuli. It is also necessary to admit that though the number of participants meeting the sampling requirements [16], their evaluations on street comfort level cannot fully represent the city population. The research outcomes provide cues on improving street visual comfort through street elements, but no evidence has been shown in relation to quality indicators such as the street width, building heights and street-width-to-building-height ratio [76]. Future studies should explore the ways of correlating both street quality and elements with human comfort perceptions at a city level, while considering the interaction between the two. Furthermore, this study utilized the relation between the rated visual comfort of streets and their characteristics as constructed by small samples to predict large-scale comfort results. Though the study adopted a rigorous calculation method and prediction model with high precision, it still cannot guarantee that the prediction results are completely consistent with the actual evaluations. In addition to methodological constraints, street functions and their traffic hierarchies may also have impacted users' comfort perceptions [77]. Therefore, it is necessary to classify street types with more detailed considerations and then compare the street comfort across types and cities in future studies.

5. Conclusions

Through integrating the objective image analysis with the subjective visual comfort evaluation, this study develops a more rigorous and efficient method for large-scale street evaluation research and broadens the boundary of human perceptive studies on public spaces at the city level. The disclosed influencing mechanisms of street visual comfort not only provide applicable cues for street design improvements but also reveal the necessity of applying design solutions that can be in response to local characteristics and development. More cities should be examined to conclude general design implications regarding street visual comfort distribution and its influential factors. It is expected that the outcome of this study and future relevant research will together contribute to the development of a locally adaptable street comfort design approach that can also be closely responsive to human perceptive needs.

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