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Analyzing the correlation between visual space and residents' psychology in Wuhan, China using street-view images and deep-learning technique

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ABSTRACT

Although previous studies have assessed the relationships between visual space indicators and urban residents' psychological perceptions, systematic research on the relationship between the urban visual space and residents' psychological perceptions is still rare. The purpose of this study is to explore the correlation between the urban visual space and residents' psychological perceptions, analyze the influence of visual space indicators on residents' subjective perceptions, and focus on whether blue-green space is influenced by walkability, enclosure, openness, imageability, and traffic flow in the mechanism of its effect on urban residents' psychology. In this study, the Fully Convolutional Network (FCN-8s) is used to segment the street view images of Wuhan. An urban perception data set is obtained by coupling the human-machine adversarial framework and the Random Forest algorithm. Based on the street view data, we design seven kinds of visual space indicators. We conduct multiple linear regression analysis on urban residents' perceptions and the mediating effect analysis of blue-green space on residents' psychology using the above five visual space indicators as mediator. The results show that there is a strong relationship between the urban visual space indicators and residents' psychological perceptions, the visual space indicators such as greenness and enclosure have a strong influence on residents' psychological perceptions and significant mediating effects of some visual space indicators occur in the process of blue-green space influencing residents' psychology. This study comprehensively analyzes the relationship and mechanism between visual space indicators and residents' psychological perception, and makes forward-looking work to further explore the complex mechanisms between visual space and residents' psychology.

1. Introduction

The urban space environment affects residents' perceptions and is closely related to people's depression and happiness [1,2]. In recent years, the effect of urban planning on residents has been highlighted [3]. As the core element of human perception, residents' psychology has received more attention. As an important reflection of the urban environment, visual space refers to residents' visual perception of urban scenes, and it impacts residents' psychology and health [4]. Therefore, it is of great significance to analyze the relationship between residents' psychology and visual space indicators for urban planning and sustainable development.

In traditional psychological research, data are collected by field investigations and questionnaire surveys [5]. Most researchers conduct questionnaires in specific places and judge the local visual indicators and psychological conditions through pedestrians' scores [6]. This method is time-consuming and characterized by high costs and low efficiency.

In recent years, with the rapid development of multi-source geospatial data [7], crowdsourced map services and geo-tagged images have become important data sources. As typical geo-tagged data, street view images enable us to perceive and understand our urban environment. In addition, street view data has been proven to accurately delineate the physical environment of our city, and it can better

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characterize residents' horizontal environmental perception than other spatio-temporal data such as remote sensing images [8]. With the development of machine learning technology, urban research that combines street view images with deep learning technologies has become more extensive and reliable [9]. Hu et al. [10] used Google Street View data and deep learning methods to classify urban street canyons to varying degrees. Ma et al. [11] quantified street visual features based on Tencent Street View data. Suel et al. [12] used street view images combined with deep learning to evaluate residents' psychology through income, education, and living conditions. Dubey et al. [13] trained a convolutional neural network model using street view images and compared six perceptual attributes of beautiful, boring, depressing, lively, safe, and wealthy. It can be seen that the combination of street view images and deep learning technology has played a constructive role in identifying and evaluating urban spatial attributes and residents' psychological perception.

In previous studies, the blue-green spaces play an important role in the mental health of residents [14,15], Dempsey et al. 2018). Blue-green spaces include greenness and blueness, where greenness represents vegetation such as trees and grass, and blueness represents water such as lakes and rivers. Gascon et al. [14] assessed the impact of long-term residence in blue-green space on depression and other negative emotions. Cohen-Cline et al. [16] took twins as the research object, and analyzed the relationship between vegetation measurement index and depression, stress and anxiety. However, most current researches only focus on the direct impact of blue-green space on residents' psychological perception [17], and there is a lack of exploration of the mechanism of blue-green space on residents' psychological perception.

The mediating effect refers to the mediator adjusting the relationship between the independent variable and the dependent variable [18]. Compared with traditional methods, mediating effect analysis can reveal complex interactions between multiple variables, and has a wide range of applications in psychology and social science [19]. Recently, some researchers have begun to apply the mediation effect analysis to urban science. Xiao et al. [20] discovered the potential mediation effect between urban green space and the wealth of residents; Jing et al. [21] explored the mediating effect mechanism between urban greening and crime fear. Therefore, it is very necessary to explore whether the mechanism of blue-green space and residents' perception is affected by the mediating effect of other visual space variables.

Although Dubey et al. [13] have created a global urban perception dataset, the training sample area in the dataset only contains two Chinese regions (Hong Kong and Taiwan), and does not involve the urban perception data of mainland China. Yao et al. [22] proposed a human-machine adversarial framework to obtain the urban perception distribution. In this study, a fully convolutional network (FCN-8s) is used to segment the semantics of street view images, and the random forest (RF) algorithm is used to fit the relationship between the visual scene features and the user ratings. The authors finally obtain an urban perception data set and then evaluate the perceptions of some cities in China. This study provides ideas for obtaining the data set and explores the relationship between visual space indicators and residents' psychological perceptions.

Can we systematically study the correlation between visual space indicators and residents' psychological perceptions? How do visual space indicators affect the subjective perceptions of urban residents? Do some visual space indicators play a role in the process of the blue-green space influencing residents' psychological perceptions? What role does it play? This has become a problem that needs to be solved urgently. Therefore, the purpose of this study includes: (1) Exploring the correlation between visual space and residents' psychological perception; (2) Exploring the effect of different visual space indicators on residents' psychology, that is, mediating effect analysis.

The main steps of this study are: first, we perform the semantic segmentation of the street view images and obtain the segmentation proportion of each ground object. Taking the feature vector that reflects the proportion of ground objects as the input, the model is trained using a human-machine adversarial framework, and then six metrics (beautiful, boring, safe, lively, wealthy and depressing) scores measuring residents' psychological perceptions are obtained. We then extract seven visual indicators of urban space: Greenness, Openness, Blueness, Enclosure, Walkability, Imageability and Traffic flow. Using multiple linear regression, we analyze the relationship between urban visual space and residents' psychological perceptions, and study the mechanism of the influence of blue-green space on residents' psychological perceptions. The results of the study further reveal the influence of urban space on psychological perception by integrating the relationship between various urban visual space indicators and residents' psychology, and provide support for relevant planners to further understand the emotional characteristics characterized by urban space and to plan urban physical space based on the corresponding results.

2. Related work

Urban visual space refers to the human eye's perception of the street scene, which can reflect the visual characteristics of the urban scene. The design and application of urban visual space has a wide range of applications in architecture, urban planning, etc. [23,24]. Naik et al. [25] used a computer vision method to quantify the changes in the physical appearance of streets and explored the relationship between physical visual components and social components. Salesses et al. [26] measured the sense of safety, class and uniqueness of cities such as Boston, New York, and Salzburg based on thousands of geo-tagged images. Li et al. [27] proved that Google Street View (GSV) is a high-quality data source for measuring street greening and openness. GSV can obtain psychological perceptions consistent with the perception of citizens.

At the method level, because the street view can truly reflect the city scene, it is often used to measure the visual physical characteristics of the city [28,29]. With the development of machine learning technology, studies that combines street view images with deep learning technology have become more popular [9]. Ordonez and Berg [30] collected densely sampled datasets of street view images in 4 cities in New York, Boston, Chicago, and Baltimore, and used deep learning technology to predict the wealth, uniqueness and safety perception within the city. Naik et al. [31] introduced Streetscore, a computer vision algorithm to measure the perceived safety of street views. Zhou et al. [32] introduced a new scene-centric database—Places. Based on this data set, a convolutional neural network (CNN) is used to learn deep features for the scene recognition task and established new results on the data set. It can be seen that the combination of street view images and deep learning technology has played a constructive role in identifying and evaluating urban spatial attributes and residents' psychological perception.

Residents' psychology for urban scenes is based on the perception of humans' experience of the place [33]. In recent years, research on urban planning and psychology has focused on finding the connection between the urban visual environment and the perception of residents. Liu et al. [34] used the Normalized Vegetation Index (NDVI) as a reflection of urban green space exposure, and discussed the relationship between neighborhood greening and human mental health. Chen et al. [35] proposed a method for aesthetic evaluation of urban green space through visual, auditory, tactile and olfactory factors. Helbich et al. [8] used street view data to analyze the distribution of vegetation and water along the street and then investigated the relationship between the urban blue-green space and the depression of the elderly. In the research on urban environment and residents' psychology, most of them explore the effects of green space and blue space on aesthetics and depression [14,36]. However, they lack the summarization of the urban visual space, including the degree of closure, openness and other related visual space elements, and lack a comprehensive exploration of the relationship and mechanism between different visual space elements and different residents' psychological elements.

There are already some studies that have given us good inspiration. Based on street view image data, many scholars have explored the impact of the scenes reflected in the images on residents' psychological perception [37,38,39,40]. Based on street view images and deep learning methods, existing studies have used indicators such as greenness, openness, and enclosure as the expression of visual space to evaluate the perception of street [11,41]. These researchers have done a lot of work in exploring how people perceive in different urban space scenarios. However, the current studies have not systematically explored the relationship between visual space and residents' psychology, and the mechanism of the effect of visual space on residents' psychology have not been mentioned yet.

Previous studies have shown that blue-green space is significantly related to the mental health of residents [42]. The visibility of the blue-green space has a positive impact on improving the residents' mental health [43]. Nutsford et al. [44] used correlation analysis based on the results of residents' mental health survey and found that the visibility of blue spaces in big cities is higher, which is closely related to the reduction of residents' psychological distress. Lachowycz and Jones [45] borrowed from the theory of social ecology, established a new theoretical framework, and summarized the current relationship between green space and health. Mpwa et al. [46] explored the relationship between blue space and health, and found that residents' exposure to blue space is beneficial to health. Dzhambov et al. [47] explored the different ways of blue-green space on mental health. The study found that different ways all play a certain role on mental health. It can be seen that the blue-green space is of great significance to the health of residents. However, in previous studies, there have been few studies on how the blue-green space affects the psychology of residents. Whether the blue-green space is affected by other mediator on residents' psychology still needs to be further explored.

Based on the above understanding, previous studies have achieved a large-scale automated measurement of urban visual space quality, and some studies have tried to explore the impact of a single feature in the visual space on the mental health of residents. However, the systematic study of the relationship between visual space and residents' psychological perception and the mechanism of visual space affecting residents' psychology is still a problem to be solved.

3. Study area and data

Wuhan is the largest city in Central China. By 2019, Wuhan has a permanent population of 11 million and a GDP of 1.6 trillion yuan. Wuhan is the political, economic, and cultural center of central China [48,49]. This study takes Wuhan's central urban area as the study area, as shown in Fig. 1. Wuhan's main areas include Hanyang, Qiaokou, Jianghan, Jiangan, Qingshan, Wuchang, Dongxihu, and Hongshan Districts.

Street view images are an important data source used in this study. Tencent map (https://map.qq.com/), one of the largest online map service providers in China, provides street view images from different angles. Based on the OpenStreetMap road network data, we select sampling points with a distance of 100 m on each main road in Wuhan. Each sampling point captures street view images (Fig. 2) from four directions (0, 90, 180, and 270 deg) at a fixed height. We finally selected 24,860 sampling points and got a total of 99,440 street view images.

4. Methodology

Fig. 3 shows the flowchart of this study: (1) Based on the urban perception model proposed by Yao et al. [22], the FCN-8s model trained by ADE-20 K data set is used to segment each street view image, and the segmentation proportion of different objects is obtained. Taking the proportion as the input, the Random Forest algorithm is used to calculate the urban perception, and the scores of six measures of residents' psychological perceptions can be obtained. (2) According to each pixel category's proportion, the greenness, openness, and other visual space indicator scores can be calculated. (3) Through a multiple linear

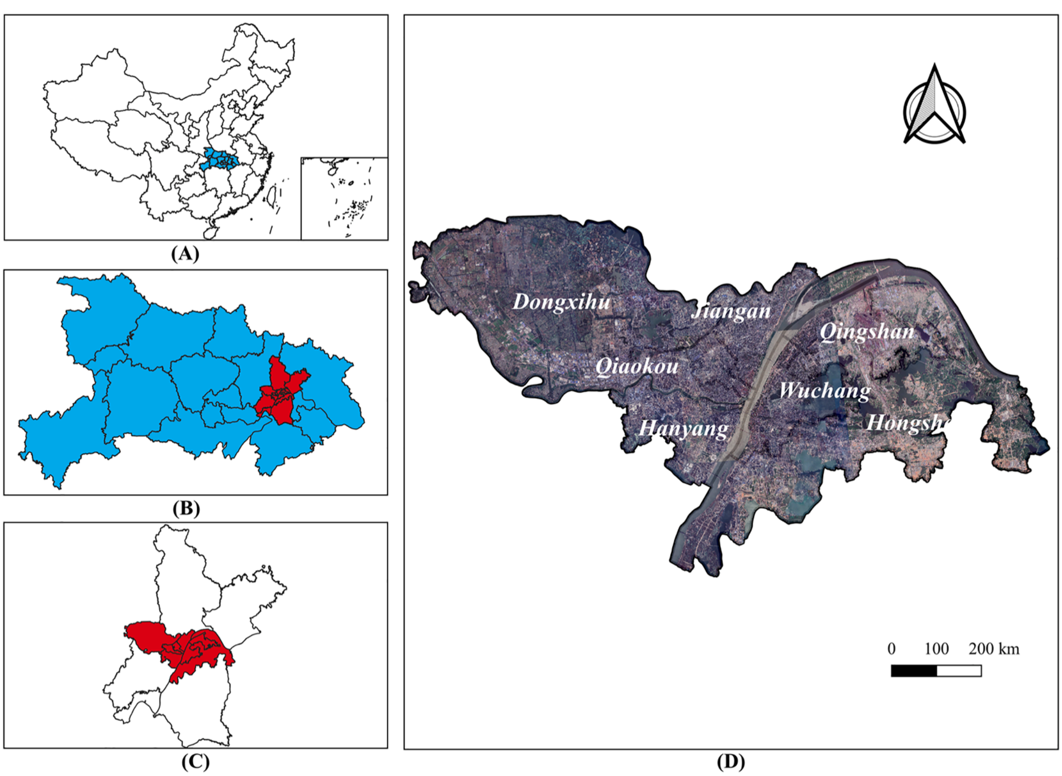

Fig. 1. The geographical location of the study area: (a) the geographical location of Hubei province in China, (b) the geographical location of Wuhan city in Hubei Province, (c) the geographical location of the study area in Wuhan, and (d) the administration of the study area.

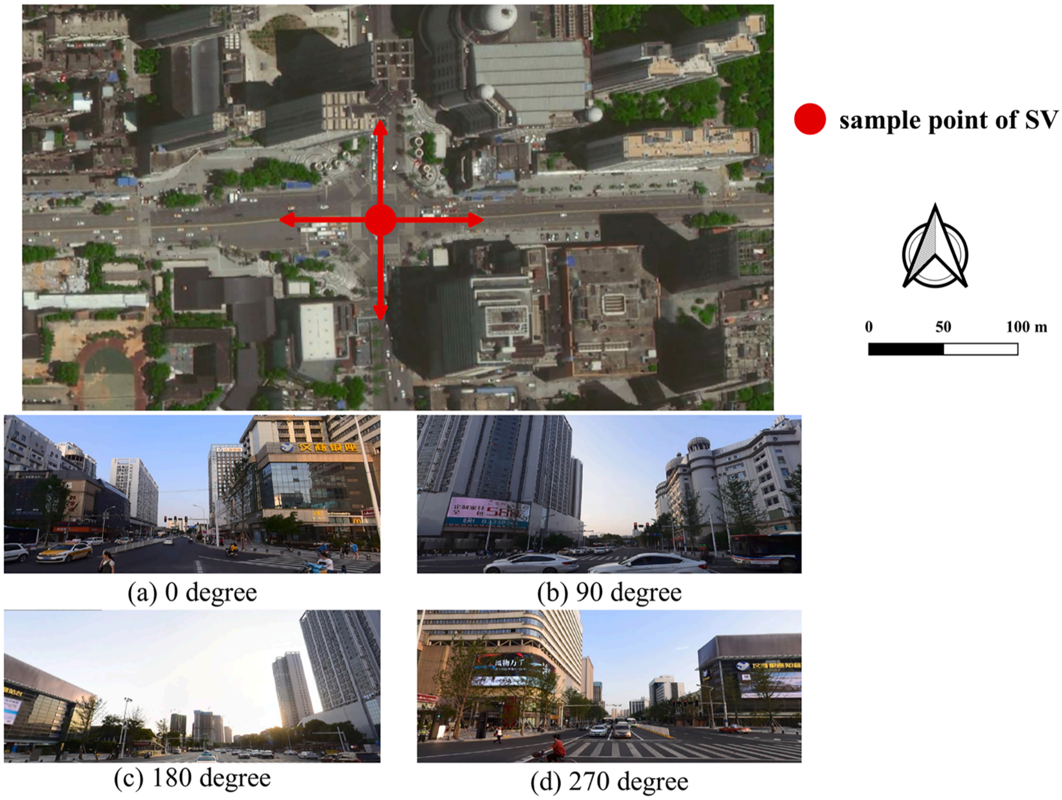

Fig. 2. An example of a shooting street view from four angles at the sample point.

regression, we analyze the relationship between the urban visual space and residents' psychological perception. (4) A mediating effect analysis was conducted to investigate the role of visual space indicators in the process of blue-green space affecting residents' psychology.

4.1. Urban perception data set based on FCN

We use FCN-8s to identify different ground objects in street view images [50]. Taking the street view images as the input, the convolution layer extracts the image features. The pooling layer reduces the dimension of the data. FCN-8s can get high-precision segmentation results. In the training process, we use the ADE-20 K annotated data set. It includes 151 categories (trees, buildings, cars, etc.). The pixel proportion of different objects in the image can be obtained by inputting the street view images into the fully convolution network.

We select 50 volunteers, including college students and company employees who are familiar with the local social environment. The volunteers' ages range from 20 to 50 years old, and the ratio of males to females is 1:1. They score the street images on a scale of 0 to 100 points on six perceptions: wealthy, safe, lively, beautiful, boring and depressing. The user scoring results will be used to build the perception score data set. Then, we use the Random Forest method to fit the relationship between the visual features and manual scoring [51]. The RF model has been proven to be effective in fitting the model [52]. The visual features, which reflect the proportion of different objects in the images, are 151-dimensional vectors based on the semantic segmentation results. The trained Random Forest model can predict the perceptions of other street scenes.

To train the Random Forest model, we use a human-machine adversarial method to ensure accuracy [22], as shown in Fig. 4. In the scoring process, when the volunteers score more than 50 images, the framework will train the random forest model based on the current scoring data set. In the next scoring process, the model will automatically give the recommended street view image scores, and the volunteers will correct the recommended scores. If there are more than 5 pictures, the model recommendation score deviates from the volunteer score by more than 10 points, then the model will be automatically retrained to adapt to the scoring process. When each volunteer has scored 600 images, the scoring ends. Since the scored images are randomly selected from the sample, the final scores of the selected images are the average value. After the above process, the model is more stable and accurate. Finally, we obtain the Wuhan perception data set.

4.2. Visual space representation based on street view data

The natural environment greatly influences human perception [53,54]. In a study on scene perception, [55] proposed the idea of extracting the visual features of street scenes to evaluate complex perceptions.

Greenness is an important part of an urban ecosystem that benefits the environment, aesthetics, recreation and economy of urban communities [56]. Besides, urban greening can make people feel happy and beautiful and have positive effects on people's emotions and psychology [57,58]. Urban greening is also considered to be a very important element in landscape design, reflecting the distribution of urban greening, so it can be used to build Greenness through trees, grass, etc.

Openness is the visibility of the sky, which determines the brightness and has a profound impact on human vision. Assessing the degree of openness can increase the attractiveness of the streetscape and enhance the comfort of public activities [11,41]. We reflect openness through the exposure of the sky.

Enclosure refers to the degree to which the street environment encapsulates pedestrians. Buildings and trees are physically separated from indoors and outdoors in urban environments. The degree of enclosure of a street has a certain effect on the mood of pedestrians [59,60,61]. Enclosure can be measured by the proportion of trees and buildings in the street view images.

Imageability is the ability or characteristic of an area that makes it

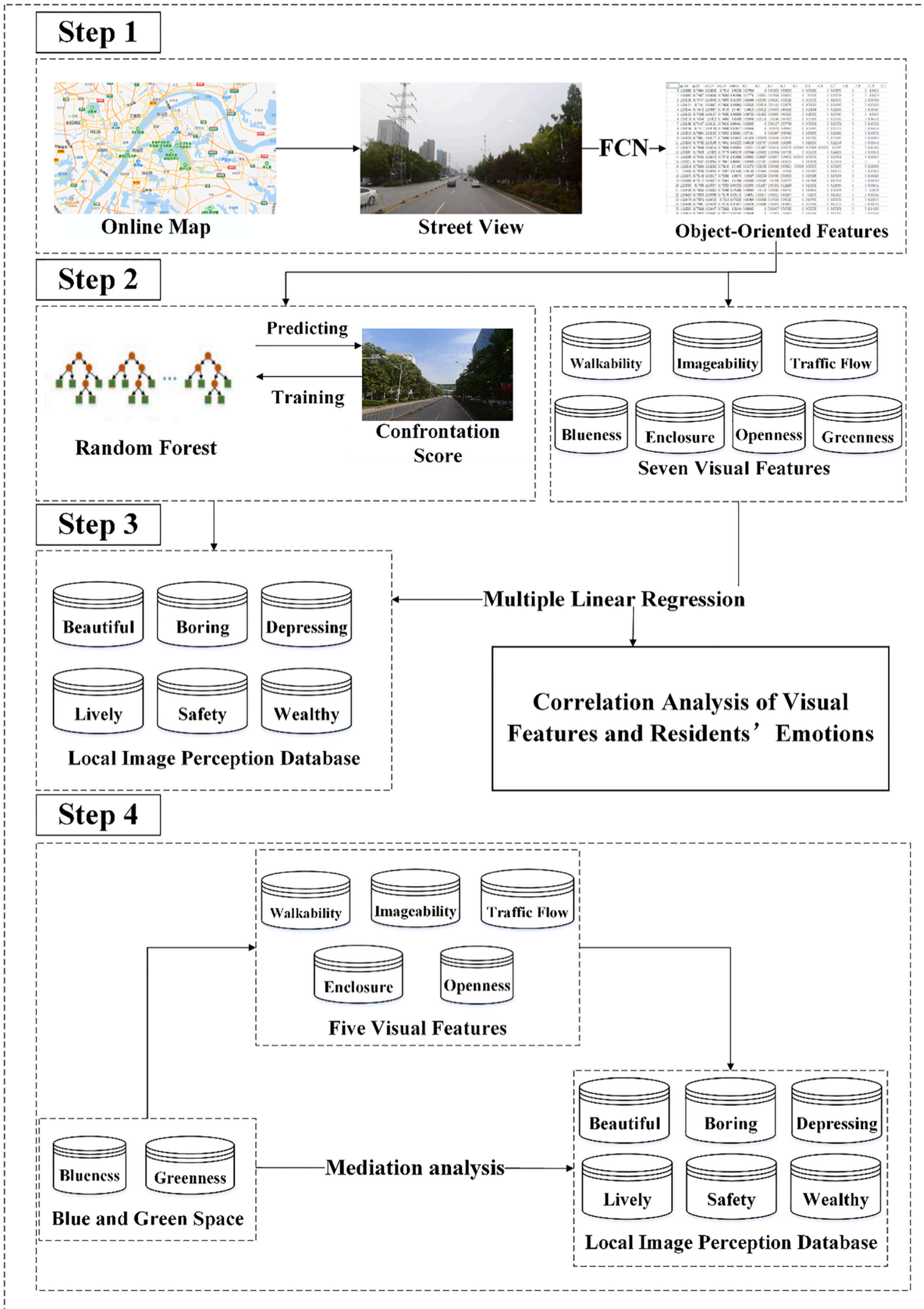

Fig. 3. The workflow of the construction of the visual space indicators and the prediction of the urban perception.

unique and memorable for city dwellers [62]. In general, some unique cityscapes may be more vivid and memorable for residents. Imageability can be measured by some signs in the street scene that can make a deep impression.

The **walkability** of streets is of great importance to pedestrians. Good walkability can increase community livability, improve public health [63]. Residential density, land use accessibility, etc. are commonly used indicators to measure walkability [60]. In order to pay attention to pedestrians' perception of the street scene, Ma et al. [11] believe that the walkability index can be reduced to the degree of visual impact of the environment perceived from a horizontal perspective, defined by the ratio of the sidewalk to the overall road.

Blueness in cities is determined by the various bodies of water. Blue space is significantly associated with residents' mental health level [43]. Studies have shown that exposure to blue space reduces psychological stress, and exposure to street blue spaces is negatively associated with depressive symptoms in older people [64]. Blueness is mainly measured by rivers, oceans, lakes and other water in street view images.

Traffic flow is mainly related to the vehicle flow and the pedestrian flow. The street's traffic flow can reflect some characteristics of the area and the surrounding area. For example, the pedestrian flow can reflect the liveliness of the area around the street. Traffic flow can be measured by vehicles and pedestrians in street view images.

We use deep learning technology to segment the street view images into 151 common visual objects. Then, we extract seven visual space indicators for further study. The seven visual space indicators are

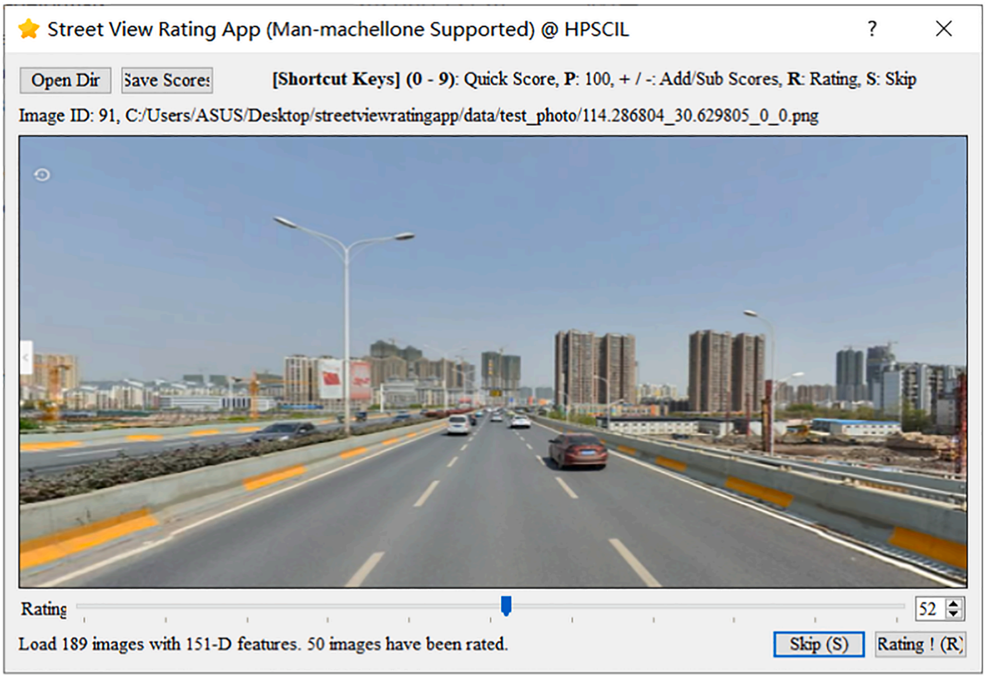

Fig. 4. Example of a human-machine adversarial framework.

described in Table 1.

4.3. *Correlation analysis of visual space indicators and residents' psychological perception*

After calculating the scores of the visual space indicators of all sample points, we conduct correlation analysis and a multicollinearity test to measure the selected indicators' effectiveness.

Table 1
Formulas for the seven indices of the visual space indicators scores.

Indicators	Formula	Expression
Greenness	$G_i = \frac{1}{4}\sum_{j=1}^{4} T_j + \frac{1}{4}\sum_{j=1}^{4} Grass_j + \frac{1}{4}\sum_{j=1}^{4} P1_j$	T_j represents the proportion of green vegetation pixels along the street,$P1_j$ represents the proportion of plants,$Grass_j$ represents the proportion of grass.
Openness	$O_i = \frac{1}{4}\sum_{j=1}^{4} S1_j$	$S1_j$represents the proportion of sky pixels.
Enclosure	$E_i = \frac{1}{4}\sum_{j=1}^{4} B_j + \frac{1}{4}\sum_{j=1}^{4} T_j$	$B_j$is the percentage of building pixels. T_j is the percentage of tree pixels.
Imageability	$I_i = \frac{1}{4}\sum_{j=1}^{4} R1_j + \frac{1}{4}\sum_{j=1}^{4} S2_j + \frac{1}{4}\sum_{j=1}^{4} P2_j$	$R1_j$is the percentage of road sign pixels,$S2_j$is the percentage of screen pixels, and $P2_j$ is the percentage of road street pillars pixels.
Walkability	$W_i = \frac{\frac{1}{4}\sum_{j=1}^{4} P3_j + \frac{1}{4}\sum_{j=1}^{4} F_j}{\frac{1}{4}\sum_{j=1}^{4} Road_j}$	$P3_j$is the percentage of pavement pixels, F_j is the percentage of street fence pixels,$Road_j$ is the percentage of road pixels.
Blueness	$B_i = \frac{1}{4}\sum_{j=1}^{4} P4_j + \frac{1}{4}\sum_{j=1}^{4} R2_j + \frac{1}{4}\sum_{j=1}^{4} S3_j + \frac{1}{4}\sum_{j=1}^{4} Lake_j$	$P4_j$is the percentage of pool pixels. $R2_j$is the percentage of river pixels. $S3_j$ is the percentage of sea pixels. $Lake_j$ is the percentage of lake pixels.
Traffic flow	$T_i = \frac{1}{4}\sum_{j=1}^{4} C_j + \frac{1}{4}\sum_{j=1}^{4} P5_j$	$C_j$is the percentage of car pixels. $P5_j$ is the percentage of pedestrian pixels.

i is the i-th point, and j is the j-th direction.

After ensuring that there was no serious multicollinearity between the visual space indicators, we obtain the regression coefficient and determine the weights of the visual space indicators for the different measures of residents' psychological perceptions through multiple linear regression. According to the regression coefficient results, we analyze the visual space indicators' influence on residents' psychological perceptions.

In the analysis of the multiple linear regression results, the mean absolute error (MAE), root mean square error (RMSE), and Pearson's R are used to measure the accuracy [65].

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{1}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \tag{2}$$

$$PearsonR = \frac{\sum_{i=1}^{n}(y_i - \overline{y_i})\left(\widehat{y_i} - \overline{\widehat{y_i}}\right)}{\sqrt{\sum_{i=1}^{n}(y_i - \overline{y_i})^2}\sqrt{\sum_{i=1}^{n}\left(\widehat{y_i} - \overline{\widehat{y_i}}\right)^2}} \tag{3}$$

n is the total number of all sample points, y_i is the perception score of the i-th sample point, $\widehat{y_i}$ is the predicted score of the multiple linear regression, $\overline{y_i}$ is the average perception score, and $\overline{\widehat{y_i}}$ is the average score of the perception prediction.

4.4. *Analysis of the mediating effect of the blue-green space on residents' psychological perception*

Considering the complexity of visual indicators and residents' psychology, this study analyzed whether the five other visual space indicators such as Enclosure are used as mediator in the process of blue-green space influencing residents' psychological perception. The mediating effect can analyze the process and mechanism of the influence between variables, in which the influence of the independent variable X on the dependent variable Y needs to be transmitted through one or more mediator M [18]. Broadly speaking, the mediation effect can be divided into three types: partial mediation effect, complete mediation effect and masking effect. Partial mediation effect refers to when independent variables affect dependent variables, part is directly affected, and part is affected by mediator M; complete mediation effect Means that the independent variables all affect the dependent variable through the mediator M; the masking effect reflects how the independent variable does not affect the dependent variable through the mediator. In this study, we use Greenness and Blueness as independent variables, six urban perception perceptions as dependent variables, and five other visual physical space indicators as mediator to explore whether the different urban perception mechanisms of Greenness and Blueness are mediated. Assuming that all variables have been processed through centralization, the following regression equation can be used to illustrate the relationship between the variables:

$$Y = cX + e_1 \tag{4}$$

$$M = aX + e_2 \tag{5}$$

$$Y = c'X + dM + e_3 \tag{6}$$

The coefficient c of Eq. (4) is the total effect of the independent variable X on the dependent variable Y; the coefficient a of Eq. (5) is the effect of the independent variable X on the mediator M; the coefficient d of Eq. (6) is controlling the independent variable. After the influence of the variable X, the mediator M is the effect of the dependent variable Y; the coefficient c' is the direct effect of the independent variable X, on the dependent variable Y after the influence of the mediator M is controlled; e1, e2, and e3 are the regression residuals. For the mediating effect model, the mediating effect is equal to the indirect effect, which is equal to the coefficient product ad. The relationship between the total effect, the direct effect, and the mediating effect are:

$$c = c^{'} + ad \tag{7}$$

When c is not significant or the sign of c' is opposite to ad, it is reflected as a masking effect. When c' is significant, c is not 0 when the partial mediation effect is, and c' is 0 when the mediation effect is complete. Therefore, this study must first test Whether the regression coefficients of greenness and blueness on residents' psychological perceptions are significant; secondly, determine whether the regression coefficients of greenness and blueness on the five mediators of openness, enclosure, imageability, walkability, and imageability are significant and whether these five mediators are significant for different residents The significance of the regression coefficient d of psychological perception; finally, according to the significant status of the direct effect $c^{'}$ of greenness and blueness on residents' psychological perception, it is further judged whether the assumed five mediators have an mediating effect in greenness, blueness and residents' psychological perceptions. There are many ways to test the mediation effect. Among them, the Bootstrapping mediating effect test method can provide a 95% confidence interval estimate of the mediating effect [66], if the interval estimate contains 0, it means that the mediating effect is not significant, and if the interval estimate does not contain 0, it means that the mediating effect is significant. In view of the fact that the Bootstrap method is more accurate than the successive stepwise test method and the Sobel method to calculate the confidence interval of the coefficient product, and has a higher test force [67], this study uses Bootstrap method to test the mediating effect.

5. Results

5.1. Influence of visual space indicators on residents' psychological perceptions

Table 2 shows the multiple regression coefficients between the visual space indicators and residents' psychological perceptions. We find that enclosure, traffic flow, and walkability affect the positive perceptions (lively, safe, and wealthy). Greenness has a negative impact on some positive perceptions (lively, safe, and wealthy) and greenness is associated with lower likelihood of the scene being labeled as "depressing" or "boring". Greenness and openness have positive impacts on the beautiful perception. Openness has a negative impact on the depressing perception.

The influence coefficients of greenness and openness on the beautiful perception are 0.780 and 0.590, respectively, which indicate that urban greening and open vision can significantly improve a city's beauty. The coefficient of blueness for the beautiful perception is 0.142, which has a positive effect on urban residents' perception of beauty. The regression coefficient between walkability and beautiful is −0.225, indicating that there is a negative correlation between walkability and beautiful.

The influence factor of greenness on the boring perception is negative (−0.505), indicating that luxuriant trees have a significant effect on eliminating residents' boredom. Urban greening can make people have a sense of pleasure and beauty and positively affect people's perceptions and psychology [13], Peter et al. 2015, [68]. The traffic flow also harms the boring perception (-0.384). Residents' boredom will obviously be suppressed when they are in an area with dense traffic and crowds. The regression coefficient between enclosure and boring is −0.335, which can reflect that area with a strong sense of closure in the city may have a certain correlation with people's sense of boredom.

The influence factor of openness on the depressing perception was −0.947, which indicates that open vision has an obvious effect on eliminating depressing perception. The influence coefficient of greenness on the depressing perception is −0.649, which also positively impacts the elimination of depressing perception.

The influence coefficient of the traffic flow on the lively perception is 0.534, which means that urban residents will feel the liveliness of the area when experiencing dense vehicles and crowds. However, greenness has a negative impact on the lively perception (−0.736), indicating that luxuriant trees would significantly reduce the liveliness of regions.

Enclosure (0.656) and traffic flow (0.461) both improve residents' safety. In areas with frequent traffic and crowds, the safety facilities are

Table 2
Regression between the visual indicators and human psychological perceptions.

Indices	Beautiful	Boring	Depressing	Lively	Wealthy	Safe
Greenness	0.780***	−0.505***	−0.649***	−0.736***	−0.842***	−0.575***
Openness	0.590***	−0.013**	−0.947***	−0.141***	−0.044***	−0.090***
Imageability	0.005	−0.020	0.011***	−0.095***	−0.101***	−0.049***
Blueness	0.142***	0.027**	−0.035***	−0.134***	−0.091***	0.033***
Enclosure	−0.064***	−0.335***	0.116***	0.625***	0.703***	0.656***
Traffic flow	−0.040***	−0.384***	0.120***	0.534***	0.317***	0.461***
Walkability	−0.225***	0.193***	0.081***	−0.316***	−0.417***	−0.207***
Constant	0.143	0.774	0.841	0.519	0.488	0.353

"*"$p < 0.100$.
"**"$p < 0.050$.
"***"$p < 0.010$.

complete, and residents' sense of danger will be reduced. Greenness (−0.575) will reduce residents' sense of safety, indicating that the area with luxuriant trees may enhance the perception of dimensional danger.

The enclosure will enhance residents' perception of wealth (0.703). High enclosure areas are mostly surrounded by buildings, corresponding to the urban CBD and other central areas. The traffic flow also has a positive effect on the wealthy perception (0.317). Areas with frequent traffic and crowds also contribute to the sense of wealth. The greenness decreases the wealthy perception (-0.842), indicating that an area with abundant trees has a lower sense of wealth.

5.2. Results of the analysis of the mediating effect of blue-green space on residents' psychological perceptions

This research conducted a series of mediating effect analysis to explore the mechanism of visual space indicators (openness, enclosure, imageability, traffic flow, and walkability) in the process of blue-green space's psychological impact on urban residents.

According to the results, we found that in the process of blue-green space affecting residents' psychology, the mediating coefficients of imageability and walkability are small and some mediating effects are

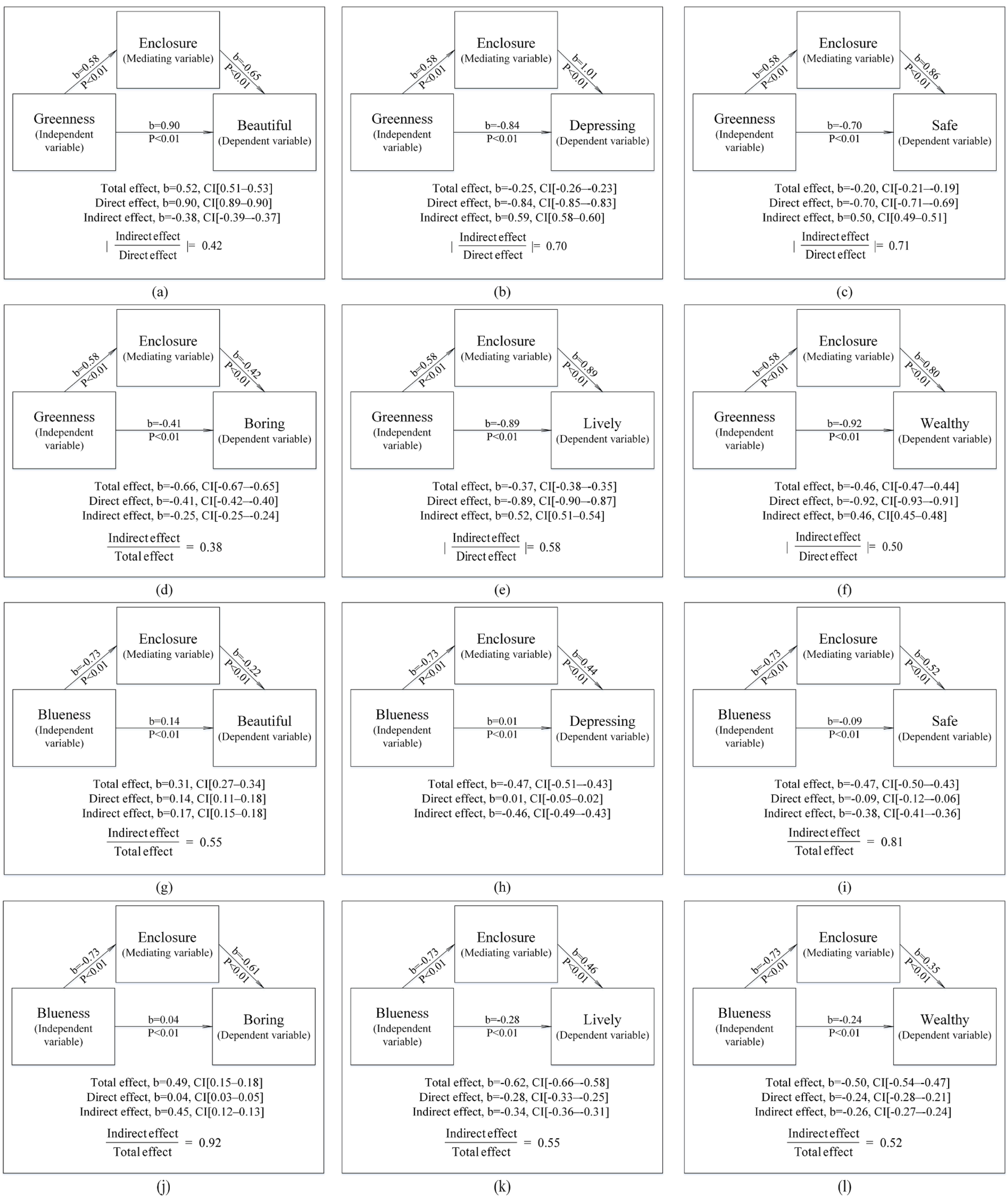

Fig. 5. The results of the mediating analysis of enclosure in the process of blue-green space influencing residents' perceptions (b is a non-standardized regression coefficient, and CI is the confidence interval of the bootstrap method).

not significant. Imageability and walkability are all related to the actual street facilities. For example, rich decoration, diverse architectural styles, and prominently visible road signs will bring good imageability [62]. Good street walkability has a lot to do with sidewalks and pavement fences [57,58,69]. Therefore, it is not difficult to understand that these indicators play a small role in the process of blue-green space influencing residents' psychology. In addition, we found that openness and enclosure have opposite mechanisms in the process of blue-green space influencing residents' psychology. Dense buildings and dense tree canopies will reduce the openness, while the enclosure will increase [11].

Thus, we only use enclosure as the mediator to analyze how blue-green spaces affect residents' psychology. With enclosure as the mediator, blue-green spaces have significant effects on the six psychological perceptions of residents. The result is shown in Fig. 5.

The direct effect value of green space affecting beautiful perception $b = 0.90$, the indirect effect value $b = -0.38$, and the masking effect occurs, indicating that the degree of enclosure inhibits the green space to promote beautiful perception. The direct effect value of green space affecting depressing perception $b = -0.84$, indirect effect value $b = 0.59$, the masking effect occurs, and the degree of enclosure can eliminate the influence of part of the green space that exacerbates the depressing perception. The green space affects the boring perception and has a partial mediating effect, and the degree of enclosure accounts for 38% of the green space's influence on alleviating boring perception. When green spaces affect positive psychological perceptions such as wealthy, safe, and lively, they all have a masking effect, and the degree of the enclosure eliminates part of the green space's reduction of wealthy, safe, and lively. A partial mediating effect of blue space affecting beautiful perception occurred, and the degree of enclosure in the blue space promotes beautiful perception, accounting for 55%. The direct effect value of blue space on boring $b = 0.04$ and the indirect effect value $b = 0.45$, indicating that closure plays a major role in the process of blue space exacerbating boredom, with an effect ratio of 92%. The direct effect of blue space on depressing perception was not significant and occurred fully mediated, and the process of blue space alleviating depressing perception was all achieved by blue space reducing confinement and thus alleviating depressing perception. The effect of blue space on affluence, liveliness and safety was partially mediated, and the proportion of the effect of enclosure in the process of affluence and liveliness was 52% and 55%, respectively, and the proportion of enclosure in the process of reducing safety in blue space was 81%.

6. Discussion

Based on the street view images, this study systematically explores the relationship between the urban visual space and residents' psychological perceptions and finds a correlation between visual space characteristics and residents' psychological perceptions and emotions. By applying a machine learning method to street view images, we design a set of urban visual space characteristics and indicators. Taking the visual space indicators as independent variables, we conduct multiple linear regression analysis on six kinds of urban perceptions and find the effects of the visual indicators on psychological perceptions through regression results.

This study finds that when residents are in an area with a high degree of greenness and openness, the beautiful perception will be improved, and the depressing perception will be suppressed. This finding is consistent with the conclusion of that exposure to blue-green space can alleviate depression in the elderly [8]. The density of trees and the openness of the space positively impact residents' pleasure and liveliness [39–40,70]. Van Herzele and De Vries [68] show that urban greening can bring people a sense of pleasure and happiness, promoting people's mood and psychology. Tang and Long [41] found that the openness of the street can increase the attractiveness of the streetscape and enhance the comfort of public activities, which is consistent with our results. We have found that high-density green spaces tend to have a lower sense of wealth, which may be the characteristics of Chinese cities different from cities in other countries. In China, the CBD in the city center is covered by high-rise buildings. These areas are expensive and the proportion of green vegetation is relatively low, so the proportion of urban greening pixels is small.

The results also show that areas with dense traffic make people feel more lively and safer in China. The commercial areas, multi-purpose mixed areas, and other lands can significantly enhance the regional liveliness [71]. Residents' sense of safety on the street is closely related to the street level activities, the connectivity between sidewalks, the types of buildings, familiarity with the current environment, and the maintenance level of facilities [72,73]. This phenomenon is worth noting that in China, residents in the center of the city tend to have a high sense of safety, which is different from locations abroad [74,72]. This result also proves that it is inappropriate to apply foreign or global urban perception data set to assess the residents' perceptions in Chinese cities [22].

We also find that the degree of the enclosure is positively correlated with residents' perceived safety in the area. Naik et al. [75] also found that well-closed streets give people the impression of high safety, thus providing residents with opportunities to interact with the society. Cai and Wang [72] found that residents in urban centers in China have a high sense of safety. The degree of the enclosure has a strong relationship with the surrounding buildings and tree density. The buildings with the high enclosure are surrounded by high-rise buildings and tall trees, corresponding to the city's urban center.

This study also analyzes the mediating effect of the blue-green space's influence mechanism on urban perception. We found that the influence of green space on depressing perception and safe perception is mediated by the degree of enclosure. The degree of enclosure in the process of green space influencing depressing perception will offset part of the green space's inhibitory effect on depressing perception, and the degree of enclosure will also alleviate the inhibitory effect of green space on the sense of safety. The dense green space can effectively alleviate people's depressing perception, but at the same time, it will affect people's stress response, thereby reducing the sense of safety [76]. And a well-closed street tends to give people the impression of greater safety [60,61]. Therefore, during street planning, lush trees can be planted at appropriate intervals to maintain the balance of street green density and enclosure.

The degree of the enclosure has a completely mediating effect in the process of blue space affecting depressing perception. The inhibition of blue space on depressing perception is to reduce the degree of the enclosure through blue space, and the reduction of enclosure degree will inhibit the generation of depressing perception. There are some mediating effects in the sense of safety, and the effect value accounts for 70% of the total effect value, indicating that the degree of enclosure occupies the main factor in the mechanism of blue space reducing the sense of safety.

To enhance the residents' aesthetic perception and liveliness and inhibit perceived depressing perception, it is necessary to increase the proportion of green space in urban planning and increase the openness of specific areas. Urban greenness and openness can make people feel happy and improve mental health. Therefore, vertical greening can be built along the community streets [77] to alleviate the tendency of depressing perception among the elderly and improve livability. Some dilapidated houses can be demolished, and the alleys can be widened to improve the openness of the area.

There are still some deficiencies in this study. First, considering that urban perception is related to many factors, such as geographical location, the mental state of urban residents, building type, etc., predicting urban perception by constructing visual indicators has limitations. Second, the study area is the central area of Wuhan. In order to enhance the universality of the conclusions, we also need to analyze a larger area.

At present, we have collected street view data in Beijing, Shanghai, Shenzhen and Guangzhou and proceeded to the next step. Third, considering that ground objects in the street view images will also have an impact on the residents' perception of the scene, in the follow-up work, we will analyze the ground objects and residents' psychological perception and compare them with our analysis. Fourth, when obtaining the urban perception data set, we considered that subjective perception varies from person to person and that the human-machine adversarial model we use can guarantee a certain degree of accuracy, so we did not define detailed perception for volunteers. In the follow-up work, we will analyze the perception differences of different groups based on factors such as age, occupation, and income. This will be our focus in the future.

7. Conclusion

Given the correlation between visual space and residents' psychological perceptions, how the visual space indicators affect the subjective perceptions, and the intermediate mechanism of blue-green space influencing residents' psychology, this study constructs an urban perception data set through the method proposed by Yao et al. [22] based on Tencent street view images of the central area of the city of Wuhan. From the multiple linear regression results, we obtain the relationships and directions of influence between the visual space indicators and residents' psychology, which provides guidance for urban planning. That is, the design of the urban visual space can regulate the psychological perceptions of urban residents. Based on the results of the mediating effects analysis, we found that the process of blue-green space affecting residents' psychological perception was influenced by mediator such as enclosure.

This study analyzes the relationship between the urban visual space indicators and residents' psychological perceptions and the mediation effect of blue-green space affecting residents' psychology. Our study finds several interesting results: greenness and openness can easily lead to an increased perception of beauty and decreased depressing perception and other negative psychological perceptions among residents, an intense traffic flow will significantly promote the liveliness of the city, and enclosure promotes the perception of safety. The remaining visual space indicators have a certain effect on the perceptions of urban residents. The blue space relieves people's depressing perception by reducing the degree of enclosure. Therefore, in future urban planning, according to the characteristics of different scenarios for different plans and designs, such as an elderly community, the relevant departments can build small-scale and vertical greening, increase the proportion of green space, etc. To better explore the relationships between visual space indicators and residents' psychological perceptions in Chinese cities, we will consider more factors and study more Chinese cities in the future. For example, we will establish urban perception data set for different Chinese cities, explore the commonalities between visual space indicators and residents' psychological perceptions in Chinese cities, and provide planning suggestions for urban development in China.

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Declaration of Competing Interest

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

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cacint.2021.100069.

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