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Associations between the quality of street space and the attributes of the built environment using large volumes of street view pictures

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Abstract

In this study, we focus on the quality of street space which has attracted high attentions. We discover associations between the quality of street space and built environment attributes through an ordered logistic model using massive street view pictures (SVPs) and data on street location, form, function and attributes. Before ascertain which built environment factors influence the quality of street space, we checked the concordance of the experts' scores, as well as correlations between different dimensions through Kappa analysis and drew the distribution map of street space quality. We found that the value of intersection over union is 85.61% for scoring the street space quality by different people. The spatial quality of more than 75% streets are in the middle level with no obvious polarisation observed in the central area of Qingdao. In addition, for street quality index, all variables are statistically significant. The sequence is as follows: near-line rate > D/H ratio > slope > length of street > distance to administrative center > POIs diversity. The D/H ratio, near-line rate, slope length of street, distance to administrative center and POIs diversity have various associations on every dimension of street quality. They can prove useful for drafting more appropriate policy measures aimed at improving street quality.

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Street view pictures, street space quality, built environment, ordered logistic model, virtual audit platform

Introduction

Streets are a fundamental component of urban public space. Street space quality refers to human perceptions of the overall environment associated with street space (Middleton, 2018; Tang and Long, 2019). Streets equipped with good spatial quality can have a positive impact on the quality of life and amenities of citizen (Zhang et al., 2019). Good street quality can also enhance social interactions among users and promote the healthy behaviour of residents (Shahideh, 2013). Previous street quality studies have looked at aspects such as coherence, legibility and linkage (Ewing and Clemente, 2013), openness (Li et al., 2017), richness and diversity (Shahideh, 2013), safety, continuity, comfort and attractiveness (Fruin, 1971), enclosure (Owens, 1993), and walkability and physical disorder (Nagata et al., 2020; Marco et al., 2015). Over the past 10 years, the increasing availability of massive street view pictures (SVPs) have prompted many researchers to try to identify street quality on a large scale (Tang and Long, 2017; Ye and Nes, 2014; Zhang et al., 2019). Large-scale studies of street quality using traditional methodologies based on surveys, field observation or interviews face limitations due to the enormous cost in time and finance (Appleyard and Lintell, 1972; Gehl and Gemzøe, 1996; Sallis et al., 1997; Shahideh, 2013; Downs and Seta, 1977; Rahimiashtiani and Ujang, 2013). In comparison, using SVPs can avoid some of these disadvantages and help assess large-scale street space quality effectively and economically. The street images which reflect real street scenes can get more accurate evaluations of street quality through repeated comparisons.

Despite these developments, street quality assessments which use massive SVPs still face some challenges. The first challenge is that image segmentation techniques still face technical limitations which have yet to be resolved. The development of image segmentation techniques supports a quantitative calculation of the visual information of SVPs, such as trees, sky, buildings, pedestrians and windows. These elements encourage the evaluation of quality through the dimensions of greenery, openness, enclosure and motorisation (Liu et al., 2017; Tang and Long, 2019; Zhang et al., 2019). However, the image segmentation techniques mainly detect objects by colour, and therefore cannot distinguish different objects with the same colour very effectively (such as the green façade and the farm) (Ma et al., 2021). In addition, it is hard to classify elements when unusual visual elements appear, such as street artwork or atypical architecture (Naik et al., 2014). Therefore, dimensions such as complexity and imageability are hard to evaluate through image segmentation techniques. Moreover, even though image segmentation techniques have been applied to evaluate the human scale (Shen et al., 2017), automated assessment studies which rely on SVPs consider only limited physical features, such as the number of small planters and the percentages of windows (Nagata et al., 2020). To overcome this shortcoming, a combination of manual scoring by experts and a virtual audit platform with massive SVPs is adopted for this study.

The second challenge for identifying street quality at a large scale is whether the ratings from the expert panels are reliable and consistent for quality estimation outcomes. People have their own individual perceptions when ranking the quality of street space. Differences in rankings across people may make it difficult for urban planners or designers to distinguish which streets need the most attention for regeneration. In previous studies, high levels of observed agreement were documented regarding signs of physical disorder, physical decay, dangerousness and street safety in neighbourhoods in the UK (Odgers et al., 2012). Experts' scoring have also been conducted for commercial streets (Ewing and Handy, 2009). However, it would be important to expand the ratings by expert panels from 'typical' streets with similar streetscapes, to all streets in a city, using SVPs.

The third challenge is to ascertain which built environment factors, which are not captured by SVPs, influence the quality of street space. It is important to connect the built environment factors with street quality because policy measures aimed at improving street quality often target the built environment. However, the assessment of built environment factors can only be conducted after resolving the issues raised by the first two challenges, namely, the enhancement of SVP assessments using expert panels and whether the ratings from the expert panels are reliable and consistent for large scale quality estimation outcomes. Therefore, this assessment is conducted after the analysis for the first two challenges is completed.

During the design of the above study, the authors also faced the question of correlations between dimensions. After considering 51 perceptual qualities of urban design, Ewing and Handy (2009)'s classic study validated five dimensions for representing street quality, namely, enclosure, human scale, transparency, complexity and imageability. However, none of the existing studies have checked the relationship between the defined dimensions. If dimensions are correlated with each other, then there may not be a need to assess all dimensions, thereby reducing the burden of calculation. It is especially crucial when comparing street quality on a large scale for various neighbourhoods or in a city. Therefore, in this study, we also checked whether the five dimensions proposed by Ewing and Handy (2009) are correlated with each other using the Kappa analysis.

Given the above, this study explores answers to the challenges identified above using massive SVPs in conjunction with data on street location, form and function for all streets of central Qingdao, China (see 'study area' and Supplement Figure S1 in the Supplementary Material for more information). First, we collected SVPs and asked a panel of experts to score the quality of streets through a virtual audit platform. Second, we checked the concordance of the experts' scores, as well as correlations between different dimensions through Kappa analysis. Third, the distribution map of street space quality was drawn. Last, we applied an ordered logistic model to explore the association between the street attributes, location, form, function and street quality. We expect our study to provide an additional means to measure the subjective qualities of the urban street environment and broaden the scope of research in discovering associations between the quality of street space and built environment attributes using massive SVPs.

In the remaining part of this paper, first, a literature review is presented to position this paper in the literature. In Section 3, the study area, detailed methods and selection of influencing factors are described. In Section 4, an empirical study of the central area of Qingdao is conducted. The last section gives the concluding remarks and potential applications and limitations.

Literature review

In recent years, there has been growing interest in the application of SVPs in studies of street quality at a larger scale (Anguelov et al., 2010; Curtis et al., 2013; Dubey et al., 2016; Griew et al., 2013; Harvey et al., 2015; Li et al., 2015; Liu et al., 2017; Naik et al., 2014; Rundle et al., 2011; Shen et al., 2017). As noted above, a major advantage of SVPs is that they can capture spatial information at the street level, which greatly lowers the cost of data acquisition. Here, we present the major studies on identifying street quality using SVPs in order to better position this study in the literature (Table 1).

Most SVPs-based studies on street quality rely on image segmentation technology such as MATLAB (Long and Liu, 2017), SegNet (Tang and Long, 2019; Ye et al., 2019), as well as artificial neural network and support vector machine (Wang and Yin, 2016; Zhang et al., 2018). Image

Table 1. Existing studies evaluating street quality through SVPs.

Source	Methods	Scale	Sample size	Regulations
Ye et al. (2019)	Uses SegNet to extract the pixels representing key elements affecting the visual quality of streets; a Java-based program to collect the expert panel's preferences on which SVPs look better via pairwise comparison; an artificial neural network to train an evaluation model to achieve a citywide evaluation	Town centre of Shanghai	140,000 SVPs from Baidu Street View	Street greenery has the highest relative importance, followed by diversity, sky view and pedestrian space in street quality
Tang and Long (2019)	Uses SegNet to extract greenery, openness, enclosure; calculate street wall continuity and cross-sectional proportion; a subjective evaluation of the street by street users	*Hutongs* (historic areas with narrow streets) in Beijing	51,356 SVPs from Tencent Map	Most *Hutongs* have a shortage of visual green, relatively more continuous wall, but with low cross-sectional ratio
Long and Liu (2017)	Analyses the colour (green) composition using MATLAB for SVP and used linear regression to analyse the factors (city size, road design, water, population density, elevation, geographic location, temperature, humidity, sunlight, etc.) influencing the greenery rate of each city	245 major Chinese cities	Over one million SVPs from Tencent Map	Longer streets in more economically developed and highly administered cities tend to be greener; (2) cities in western China tend to have greener streets
Wang and Yin, 2016	Uses Artificial Neural Network and Support Vector Machine to develop an algorithm to measure the proportion of sky and then to see how the proportion of sky is associated with the presence of trees and building heights along the streets using correlation tests	Buffalo	3592 panoramic images from Google Street View	Sky area that people can see; a street is influenced by what is on both sides of the street, such as trees and buildings, and it also has influence on street walkability

(continued)

Table 1. (continued)

Source	Methods	Scale	Sample size	Regulations
Salesses et al. (2013)	Scores each image using the number of times it got selected over another image for evaluation of street quality in terms of perceptions of safety and uniqueness	New York City and Boston in the United States; Salzburg and Linz in Austria	4136 SVPs from Place Pulse or Google Street View	Positive and negative perceptions cluster more strongly in the two American cities than in their European counterparts
Hara et al. (2012)	Studies sidewalk accessibility through crowdsourcing by creating an interactive online labelling tool in Javascript, PHP and MySQL.	Neighbourhoods in Los Angeles, Baltimore, Washington DC and New York City	100 SVPs from Google Street View	Showed that untrained crowd workers can locate and identify sidewalk accessibility problems with relatively high accuracy (~80% on average) using SVPs
Odgers et al. (2012)	Virtual systematic social observation (SSO) study	1012 neighbourhoods in the United Kingdom	Not explained	High levels of observed agreement were documented for signs of physical disorder, physical decay, dangerousness and street safety
Rundle et al. (2011)	Compares neighbourhood measures coded from SVPs with those based on field observations	37 blocks	140 SVPs from Google Street View	High levels of concordance for 54.3% of the items. Measures of pedestrian safety, motorised traffic and parking, and infrastructure for active travel had relatively high levels of concordance

Note: SVPs: street view pictures.

segmentation technology has limitations for studying street space quality because it focuses on the proportion of physical features (such as buildings, windows, roads, trees and bicycles) and other limited dimensions to represent street quality and fails to directly reflect street quality in a comprehensive manner. For instance, Long and Liu (2017) chose greenery to reflect street quality in Chinese cities, while (Ye et al. 2019) applied street greenery, diversity, sky view and pedestrian space to represent street quality, drawing on 140,000 SVPs from Baidu Map. (Tang and Long 2019) collected 51,356 SVPs from Tencent Map and used street greenery, wall continuity and cross-sectional ratio to assess street quality. Wang and Yin, 2016 used the proportion of sky to evaluate the street quality in Buffalo, drawing on 3592 SVPs through Google Street View.

There are a handful scholars who used other methodologies in SVPs-based street quality identification in order to capture additional dimensions. For instance, Salesses et al. (2013) studied perceptions of safety and the uniqueness of image based on the number of times it got selected over another image. A crowdsourcing approach was proposed by Hara et al. (2012) to evaluate sidewalk accessibility of neighbourhoods in Los Angeles and New York City using 100 SVPs from Google Street View. Unfortunately, none of these previous studies considered the correlation among the selected dimensions. In addition, the ranking agreement for the suggested approaches such as crowdsourcing or imaging comparisons were not checked, which could be a potential weakness if the evaluation of street qualities varies across people. These gaps for evaluating street space quality may create difficulties for further planning. The only studies which checked the consistency of scoring were by Odgers et al. (2012) and Rundle et al. (2011), but Rundle et al. (2011) only compared the agreement between the SVPs and field observations. Odgers et al. (2012) checked the agreement for only street safety and physical disorder.

In addition, few studies have studied the association between street quality and built environment attributes. Long and Liu (2017) used linear regression to analyse the influence of city size, road design, water, population density, elevation, geographic location, temperature and humidity on the greenery rate of each city. Wang and Yin, 2016 checked the relationship between the proportion of sky and the presence of trees and building heights along the streets. However, only a very limited range of attributes for either street quality or the built environment have been used to explore the association between them. Further research on the associations between street quality and other built environment factors is still needed.

To fill some of these research gaps, this study provided a virtual audit platform to support large-scale scoring by experts for the five dimensions of enclosure, human scale, transparency, complexity and imageability. Then, the reliability of the rankings by experts was checked, and the correlations among the dimensions were assessed. This process enabled us to transform information from SVP images into objective measurements of the perceptive quality of streets. The associations between built environment and street quality were also explored by adding more built environment aspects, including street forms, street attributes, street locations and street function. This study can provide a guide to support street quality identification in the future.

Data and methods

Methods for qualifying the street space quality

Simplifying the street. The road/street data, including urban roads, pedestrian roads, narrow pathways and alleys, from the Tencent map have the advantage of fast updating and high spatial coverage, as it covers the whole country. To prepare for the analysis, the streets were simplified in the ArcGIS platform according to Long and Liu (2017) before obtaining SVPs. After simplifying, 12,972 streets remained, with a total length of approximately 3893 km (an average of 0.31 km)

Obtaining SVPs. Street view pictures were downloaded from Tencent Map (http://map.qq.com) through the application programming interface (API). We used the centre point of every street as the observation point for this street. As a result, 51,888 images covering 12,972 streets in the study area were captured in Python from https://map.qq.com (accessed on November 18, 2017).

Tagging the quality score through virtual audit. We developed a virtual audit platform containing 16 items of street space quality for the five dimensions of enclosure, human scale, transparency, complexity and imageability (see Supplement Table S1 in the Supplementary Material for details of each dimension; see Supplement Figure S2 in the Supplementary Material for images of the four directions). For each street observation point, experts were shown four SVPs, representing the four directions of left, right, front and back. For each dimension, the experts were asked to give a score of 1 if there is at least one item of street space quality on the street observation point in the four SVPs and 0 if there is no item for that street observation point. The street quality index (SQI), which refers to the total score of five dimensions, is proposed to represent the comprehensive street space quality. The SQI value goes up to 5 and is at least 0.

Specification of the influencing factors. The built environment factors expected to influence perceptions of street quality include street forms, street attributes, street locations and street functions, calculated from road/street data, building information, digital elevation models (DEMs), points of interest (POIs) and urban administrative centres. Supplement Table S2 contains the influencing factors, data, source and calculation methods. As other factors are common to other studies, here we only explain the near-line rate and D/H ratio, which are two main elements related to the layout of the street space. The near-line rate is the proportion of an edge that intersects a façade and thus forms a street wall, reflecting street wall continuity (Harvey et al., 2015). High near-line rate means less 'dead space' between buildings, such as vacant lots and parking lots (Ewing and Handy, 2009). In particular, the near-line rate of the street influences the continuity of the street space, and the D/H ratio affects the enclosure of street space (Im, 1987; Kim and Kim, 2019; Handy et al., 2002). In this study, for each street, the near-line rate is reported as the average of the two sides. D/H ratio is the ratio of the width (or distance) of an open space (D), such as public squares and streets, and the height of the surrounding buildings (H) (please see 'Methods for qualifying the street space quality' in the Supplementary Material for more information about simplifying the street, obtaining SVPs and selecting the influencing factors).

Methods to address the challenges regarding street space quality

Interrater evaluation. We set up a professional group of five volunteers with urban planning, urban design or architecture backgrounds and then trained them using a guidebook which explained the meanings and demonstrated the images of all 16 items under the five dimensions. The assessment was conducted on a virtual audit platform. In order to prevent bias, the criteria for selection of the five volunteers was that they must have at least 3 years of professional studies in their respective field; socio-demographic factors such as gender, age and economic status were not considered in the selection process. For interrater evaluation, we randomly selected 264 investigation points in the study area and used intersection over union (IoU), defined as the size of the intersection divided by the size of the union of the sample sets, to gauge the similarity and diversity of scoring results. We verified the concordance of the manual scoring for 85.61% of the streets.

Kappa analysis. Because the variables of the five dimensions used in this study are dichotomous, we first conducted a Kappa coefficient analysis to check the correlations between the enclosure, human scale, transparency, complexity and imageability. This is to check whether the five selected dimensions are suitable and is an important basis for further measuring street quality.

Associations of the built environment with quality of street space. We applied the ordered logistic regression (logit) model to explore the correlation of built environment factors and street quality (see 'logistic regression model' in the Supplementary Material for detail information). The ordered logistic regression is a promising tool due to its simplicity and fast computation time (Kropat et al., 2017). Based on this method, Yuko et al. (2009) studied the relationships of cancer pain with various factors that prevent pain control. Yang et al. (2019) applied the ordered logistic regression model to study the relationship between sleep quality and four indicators of Eysenck personality for different age groups. In terms of the built environment, Berg et al. (2016) examined the association between feelings of loneliness and built environment attributes.

The methodological framework of this study is illustrated below:

Results

Interrater evaluation outcomes

To check the concordance of manual scoring for the experts, we randomly selected 264 investigation points in the centre of Qingdao, see Figure 1 above. The scoring for 226 of them was consistent among different scorers in all dimensions. Only 38 points were inconsistent (with enclosure appearing 9 times, human scale 21 times, transparency 5 times and imageability 4 times). The IoU is 85.61%, which indicates that the manual scoring had a high concordance (see the 'Interrater evaluation outcomes' in the Supplementary Material for more information).

Street quality spatial distribution

The result of the Kappa analysis is shown in Figure 2. The dimensions of enclosure, human scale, transparency, imageability and complexity are relatively independent of each other; thus, it is reasonable and feasible to evaluate the quality of street space from these dimensions.

For the spatial distribution of street quality (Figure 3(a)–(f)), the average SQI in the central area of Qingdao is 1.73, and the number of streets with SQI values of 0, 1, 2, 3, 4 and 5 accounts for 4%, 38%, 39%, 15%, 3% and 1% of the total number of streets, respectively. Most streets with SQI 5 are distributed in the Hong Kong Central Road township. The streets with SQI 4, 3 and 2 are mostly located to the north of the streets with SQI 5.

In addition, among the five dimensions, 54.93% of streets in the centre of Qingdao have human scale, while 53.94% have transparency and 43.54% have complexity. The imageability (12.48% of all streets) and enclosure (9.03% of all streets) are relatively low; thus, improving the imageability and enclosure in street design could be important for improving street quality. The Middle-Southwest district has a better street quality in every dimension except in the dimension of enclosure. The spatial distribution of street quality not only provides an efficient way to assess street quality at a large scale, but can also set a baseline to study the associations of built environment with quality of street space.

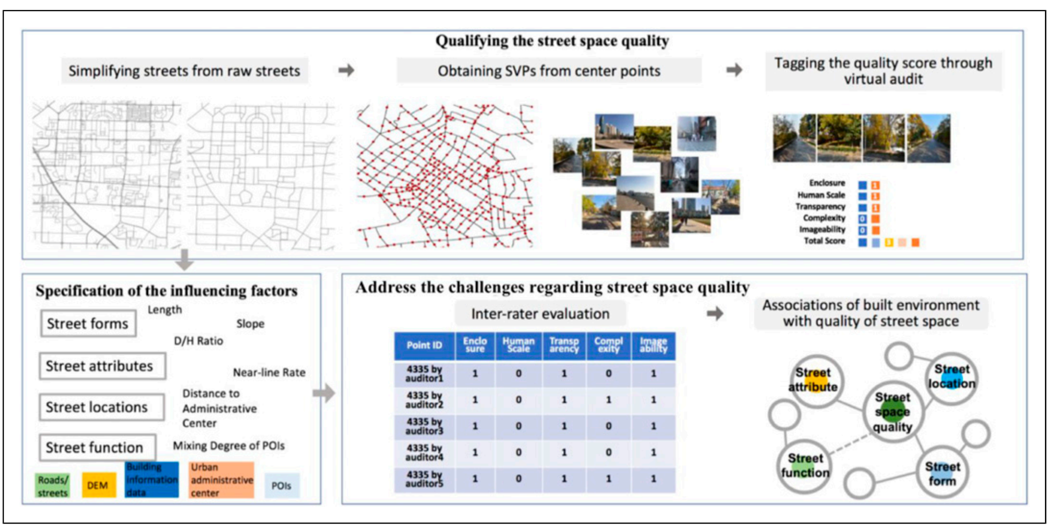

Figure 1. Methodological framework.

Figure 2. Correlation of five dimensions related to street space quality.

The associations of built environment with quality of street space

We further apply the ordered logistic model to explore the correlation between street form, street attribute, street location, street function and street quality. Figure 4 shows the odds ratio and the colour (the orange colour signifies that the coefficient is significant under the 0.1 level). For SQI, all variables are statistically significant. The sequence is as follows: near-line rate > D/H ratio > slope > length of street > distance to administrative centre > POIs diversity. Diversity of POIs refers to how diverse the POIs are in a particular street. For the enclosures, all variables are statistically significant, except the slope. The impact of the near-line rate is the most important for enclosure, followed by the POIs diversity. This is consistent with the findings of Ewing and Clemente (2013), which suggested that psychologically a high near-line rate offers 'a sense of enclosure'. The D/H ratio has a negative impact on the enclosure. Regarding the human scale, it is similar to enclosure in that all variables are statistically significant except the slope. The POIs diversity has the largest odds ratio value, followed by the D/H ratio. The near-line rate, length of street, distance to administrative centre and POIs diversity have a negative impact on human scale, which means increasing these variables can reduce the human scale. In addition, in line with previous studies, this study also found that the length of street is negatively associated with human scale. For instance, Moughtin (1991) suggested that the upper limit for uninterrupted length of street is probably in the order of 1500 m to one mile, and beyond distances of this order, human scale is lost. According to Jacobs (1961), short streets can create more diversity and humane space. With regards to the distance to administrative centre, streets near the city administrative centre may have lower human scale because of the type of construction or land use associated with central areas, for example, large-scale office buildings or government offices. The POIs diversity represent the mixed function of streets and was expected to have a positive impact on human scale,

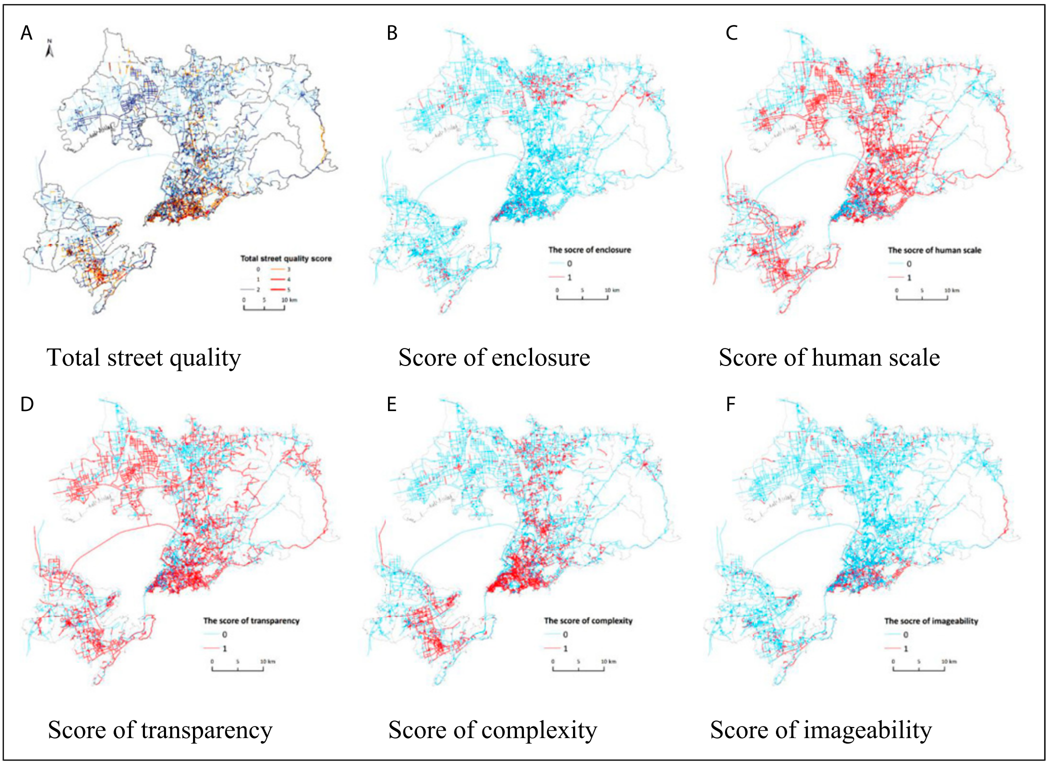

Figure 3. Distribution of SQI and score in five dimensions in the central area of Qingdao. The associations of built environment with quality of street space. (a) Total street quality. (b) Score of enclosure. (c) Score of human scale. (d) Score of transparency. (e) Score of complexity. (f) Score of imageability

but contrary to expectations, the odd ratio was negative. After checking the SVPs with POIs with a higher degree of diversity, we found there are indeed insufficient human scale elements such as pedestrian space, street furniture and public art. Furthermore, the limited pedestrian space is occupied by ground level parking for automobiles. For transparency, the D/H ratio, near-line rate and POIs diversity are statistically significant, but the slope and length of the street are not. For complexity, the sequence is as follows: distance to administrative centre > POIs diversity > D/H ratio. The impact of the POIs diversity is positive, while the other two significant variables are negative. In terms of imageability, the D/H ratio, near-line rate, slope and POIs diversity are statistically significant. An increase in the POIs diversity and the slope can increase the imageability.

Discussion and conclusions

Discussion

Our study builds on the classic study by Ewing and Handy (2009) in that it uses the five dimensions of enclosure, human scale, transparency, complexity and imageability to assess street quality. Through Kappa coefficient analysis, we find that these dimensions are relatively independent of each other. This can be viewed as further confirmation that these dimensions may be used to quantify street quality.

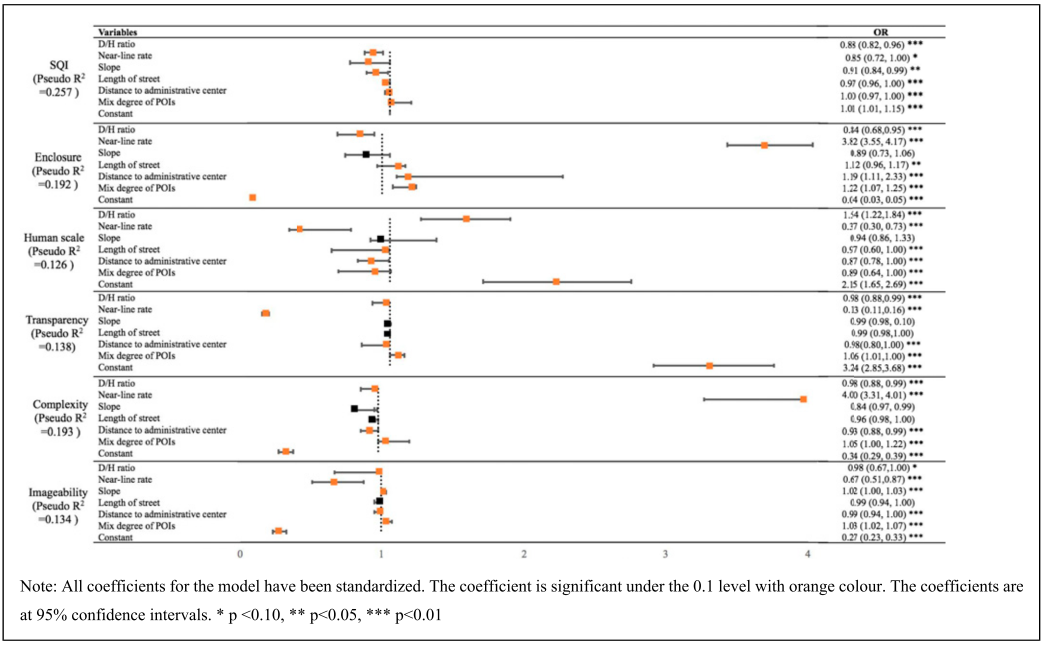

Figure 4. Forest plot from ordered logistic model on the associations between street space quality and the built environment. *Note.* All coefficients for the model have been standardised. The coefficient is significant under the 0.1 level with orange colour. The coefficients are at 95% confidence intervals. * p <0.10, ** p<0.05, *** p<0.01.

Our study broadened the experts' scoring to all street categories in the city of Qingdao, China. We found that the expert panel had high agreement in assessing all city streets, as reflected by IoU = 85.61. Higher levels of agreement were reached for transparency and imageability, but a lower level of agreement was reached for the human scale. In order to prevent a biased selection of raters, Odgers et al. (2012) recruited individuals who have living and working experience in Britain, as it was assumed that these people would be in the best position to calibrate their assessment of local neighbourhood conditions. They also held a 30 hours training for recruited individuals and pre-selected 20 neighbourhoods to check the level of agreement and found that this training resulted in high agreement between the recruited individuals. In the further studies, we plan to engage experts who have living or working experience from the study area to see whether this affects the level of agreement in the assessments.

Regarding the analysis of built environment factors, we suggest that our findings can guide urban design practice in the following ways. First, increasing the POIs diversity can improve the quality of the street from the perspective of multiple dimensions. As increasing the diversity of POIs may have a negative impact on human scale, additional measures, such as expanding outdoor catering and sidewalks, should be integrated in the design of the street. Second, the study found that there is a lack of enclosure and imageability in Qingdao. In order to enhance enclosure, more continuous street walls should be built. But considering that the high near-line rate may have a negative impact on imageability, it is necessary to avoid monotonous walls when increasing continuous street walls and to take into consideration the colour, shape, height and façade of roadside buildings. Third, reducing the length of streets can increase the quality of the city from the perspective of multiple dimensions. During urban regeneration projects, the length of other streets, as well as urban arterial roads, can be decreased by planning smaller community sizes. In addition, it may be desirable to keep long streets only for streets with a good enclosure. Fourth, because the street quality near the administrative centre is relatively low, more human scale facilities should be provided. These findings have a profound significance for planning street quality improvements.

Conclusion

The current study looked at the spatial distribution of street space quality taking the central area in the city of Qingdao, China, as our area of investigation. Our study demonstrated an alternative approach to assessing street quality using SVPs by examining the reliability of ratings from an expert panel using a virtual audit platform and checking the associations of built environment factors with the quality of street space using an ordered logistic model. It found that the manual scoring by experts resulted in a high degree of consensus. Furthermore, we confirmed that the dimensions of enclosure, human scale, transparency, complexity and imageability are independent of each other in reflecting the street space quality.

In Qingdao, more than 75% of streets in the central area of Qingdao are at the middle level, and the highest SQI value is concentrated in the southwestern area near the coast or the new development areas. However, the city's streets had relatively low scores in the dimensions of enclosure and imageability. The analysis found that all built environment variables are statistically significant, with the following sequence: near-line rate > D/H ratio > slope > length of street > distance to administrative centre > POIs diversity to SQI. A higher near-line rate can bring higher street complexity and lower human scale and transparency. The POIs diversity can improve the quality of the street from the perspective of multiple dimensions. During urban regeneration, the length of other streets can be reduced by making smaller blocks or communities.

This work expands the range of methodologies for discovering associations between the quality of street space and built environment attributes using massive SVPs. The study results have the following potential applications. First, the study verifies the use of the dimensions of enclosure, human scale, transparency, complexity and imageability to study street quality at a large scale, city level. Second, it proposes a straightforward method to assess street quality through a virtual audit platform and an expert panel. Third, the study informs the associations between the built environment and street quality. These associations can be applied to street design and management to improve the quality of the living environment for citizens. Fourth, it provides the local government with an objective assessment of street quality in the centre of Qingdao, which can help urban managers and planners determine the critical aspects and precise positions of street space for further urban design. Fifth, the study's outcomes can be used as supplementary information for future studies in a diverse range of subjects, including residents' route choice, travel time and public health.

Limitations and future steps

There are still limitations which require further exploration in the future. First, evaluating the street space quality by SVPs involves subjective valuations. Second, the pictures were taken at specific times of day. Third, this paper only focuses on the attributes of the street itself but fails to pay attention to the surrounding built environment, including land use, pedestrian volume and other factors, which may have a bearing on the street quality.

Further research could be done to extend this study in the following directions. In this study, we built a virtual audit platform to link physical features to the scoring of street quality by a panel of experts. The outcomes of the manual scoring using the virtual audit platform can form the basis for further machine learning approaches. Such machine learning approaches can be applied to quantify street quality in more cities in China and to check whether the associations of built environment with the quality of street space from Qingdao are suitable for other cities.

Declaration of conflicting interests

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Supplemental Material

Supplemental material for this article is available online.

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