Wellbeing, Space and Society 8 (2025) 100247

Contents lists available at ScienceDirect

Wellbeing, Space and Society

journal homepage: www.sciencedirect.com/journal/wellbeing-space-and-society

Is perceived safety a prerequisite for the relationship between green space availability, and the use and perceived comfort of green space?

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ARTICLE INFO

Keywords:
Green space availability
Street view
Green space usage
Perceptions of neighbourhood safety

ABSTRACT

In recent years, many researchers have argued that both the availability of green space (GS) and perceived neighbourhood safety may be prerequisites for the use of GS, but empirical findings remain inconsistent. This study explores how perceived neighbourhood safety moderates the associations between the availability of neighbourhood GS and residents' use of GS, using survey data collected in Guangzhou, China. The Normalised Difference Vegetation Index (overall amount of greenness), park accessibility and a measure of Street View Greenness (eye-level greenness) were used to estimate two types of GS availability (overall vs. eye-level). As shown by the results of the multilevel models, eye-level greenness was positively associated with the use of and perceived comfort of GS for those respondents with a higher level of perceived neighbourhood safety; it was negatively related to the use and perceived comfort of GS in the case of respondents with a lower level of perceived neighbourhood safety. In addition, the overall amount of greenness was positively associated with the use and perceived comfort of GS regardless of the level of perceived neighbourhood safety. Our findings suggest that perceived safety may be a potential prerequisite for positive associations between the availability of GSS at eye level and the use of and perceived comfort of GS.

1. Introduction

Many cities across the world have invested in urban green space (GS) to enhance people's quality of life (Kabisch et al., 2015; Klemm et al., 2015; Samus et al., 2022). A higher availability of urban GS can decrease stress and promote physical activity and social cohesion, which makes it an effective planning intervention for improving people's health (Smith and Turner, 2023; P. Wang et al., 2021). It may also provide co-benefits regarding the ecosystem, such as mitigating the effects of air pollution, heat stress, and flooding (Pinto et al., 2022). However, most of the health benefits associated with GS can only be realised when urban residents are physically or visually exposed to GS (McEachan et al., 2018; Ye et al., 2019). While GS can enable people to feel a sense of detachment from their current everyday surroundings and fulfil their desire to be in contact with nature, which can reduce stress levels (Kaplan, 1995), people have to be able to use, view and appreciate the GS in order to gain such benefits (Grahn and Stigsdotter, 2010). In this context, improving people's perception of GS as satisfactory (e.g. perceived safety, comfort, and aesthetics) can be regarded as an urban planning priority because it increases the usage of GS and improves the health of the population (Van den Berg, 2017).

Hence, perceiving GS as satisfactory is usually associated with both individual and environmental factors (Fossa et al., 2023; Gunnarsson et al., 2017). Individual factors such as age and gender may play

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https://doi.org/10.1016/j.wss.2025.100247
Received 6 September 2024; Received in revised form 3 February 2025; Accepted 27 February 2025
Available online 28 February 2025

important roles in influencing the use of GS (Sang et al., 2016). Negative environmental factors (e.g. environmental degradation, including traffic and air pollution) may also discourage people's use of GS (Gunnarsson et al., 2017), while positive environmental factors, such as higher availability of GS, positively relate to people's use of and perceptions of GS as satisfactory (van den Berg et al., 2017; Wu et al., 2019; Zhang et al., 2023). The availability of GS is usually understood as meaning the amount of GS or level of greenness within a given area (e.g. the number of parks or trees) (Markevych et al., 2017; Nordbø et al., 2018; WHO, 2016). Several explanations have been offered for the association between GS availability and the use of and perception of GS as satisfactory. First, higher levels of GS availability mean that GS resources are more abundant, and thus, people may find it easier to access GS within their neighbourhood, assuming that other conditions are the same (Bloemsma et al., 2018; Li et al., 2015a). Second, the higher the level of greenness, the more likely it is that it will be appreciated by residents, as greenness is also positively associated with the quality and aesthetic of vegetation (Memari et al., 2017; Stoltz and Grahn, 2021; Yakinlar and Akpinar, 2022; Zhang et al., 2021). Previous GS-related studies have mainly focused on large GSs, such as urban parks, while only a few have investigated small GSs within residential neighbourhoods (Tu et al., 2020; P. Wang et al., 2021; Wendel et al., 2012; Zhang and Zhou, 2018). As the space available at street level tends to be relatively narrow and thus cannot accommodate a large amount of vegetation, the GSs found on the streets are usually smaller (Wang et al., 2021c). Therefore, these green spaces are more accessible and more likely to be noticed by people going about their daily activities, which may also be important for people's well-being (Wang et al., 2021c).

Existing studies have mostly examined the independent association between the availability of GS and the use of and perception of GS as satisfactory (e.g. perceived comfort) (Kondo et al., 2018; Navarrete-Hernandez and Afarin, 2023; Perez-Tejera et al., 2022; Wu et al., 2019). However, environmental safety may also affect GS usage, and GS may not be used very frequently by residents if a neighbourhood is perceived to be unsafe (Campagnaro et al., 2020; Fermino et al., 2013; Fisher et al., 2021; Fongar et al., 2019; Groshong et al., 2020; X. Li et al., 2015b; Mouratidis, 2019; Sang et al., 2016; Tzoulas and James, 2010). Therefore, the effects of the availability of urban GS on the use of and perception of GS as satisfactory may be moderated by individuals' perceptions of neighbourhood safety (Browning et al., 2022; Lee and Maheswaran, 2011). It is possible that, if they have low levels of perceived safety, people may avoid urban GSs (Sreetheran and Van Den Bosch, 2014). Urban GS can provide cover for criminal gangs, and some types of crimes may occur more often within GSs in certain areas (Foster et al., 2016; Sreetheran and Van Den Bosch, 2014). Wendel et al. (2012) found that having GS available may encourage people to access it only if the environment is relatively safe, and therefore suggested that it may be necessary to understand people's perceptions of how safe they believe the local area to be, in order to evaluate the association between neighbourhood GS and the use of GS. Similarly, Campagnaro et al. (2020) pointed out that people preferred to visit and use GSs within what they perceived as a safe environment.

However, existing studies have produced inconsistent findings regarding the moderation effect of perceived safety on the association between GS availability and usage (Campagnaro et al., 2020; Fermino et al., 2013; Fisher et al., 2021; Fongar et al., 2019; Groshong et al., 2020; Hong et al., 2018; Jansson et al., 2013; Li et al., 2015; Mouratidis, 2019; Sang et al., 2016; Tzoulas and James, 2010). While some studies have found evidence that perceived safety matters (Hong et al., 2018), others have concluded that it has little or no effect (Sreetheran and Van Den Bosch, 2014). In recent years, it has become apparent that the different ways in which GS is measured may also explain these inconsistencies (Browning et al., 2022; Labib et al., 2020; Reyes-Riveros et al., 2021; Tu et al., 2020; Wendel et al., 2012). One of the most common methods used to assess GS availability is by using remote sensing data, for example, the NDVI (normalised difference vegetation index) (Markevych et al., 2017; Nordbø et al., 2018). However, this type of method may be unable to accurately reflect the availability of visible GS (Jiang et al., 2016). Traditional methods of assessing visible GS include the questionnaire (Takano et al., 2002) and the social observation method (De Vries et al., 2013), but both of these are costly and time-consuming (Wang et al., 2021a–c). Recently, due to advances in machine learning and online street view services, such as Google Street View, empirical studies have started to explore the possibility of estimating visible GS from street view images (Kang et al., 2020; X. Li et al., 2015).

This study examines the relationship between GS availability within neighbourhoods, the use of GS and the perceived comfort of GS (a proxy for the perception of GS as satisfactory) using street view data, satellite imagery data and survey data from Guangzhou, China. It extends previous research in two ways. First, it contributes to existing work by using street view data and satellite imagery to assess two aspects of GS (the eye-level view and the overhead view). This allows us to explore the heterogeneity in the association between different aspects of GS and the use of and perceived comfort of GS. Second, it also considers the role of perceived neighbourhood safety in moderating the associations between GS availability and the use of and perceived comfort of GS. Hence, it advances the current theoretical understanding of the moderating role of perceived safety in promoting or hindering the use of and satisfactory perception of GS as satisfactory.

2. Methodology

2.1. Survey data

This study used survey data collected by Sun Yat-Sen University. It was obtained via a survey conducted between March and August 2017, designed to gain insight into residents' quality of life in Guangzhou. The survey targeted adults living in the inner-city area, so respondents had to be aged 18 or above and not students. The city's total population was approximately 14 million in 2018, and the number of crimes committed totalled 218,600 (crime rate = 1.67 %), according to the official crime statistics (Xu, 2018). The urban GS ratio in the urban area of Guangzhou was 41.8 % in 2016 (Guangzhou Statistic Department, 2017). We focused on Guangzhou, which is the largest city in southern China, because, due to the growth in urban green spaces within the city, it was nominated as one of the most important national garden cities in China. However, Guangzhou is quite dense and highly populated, so the green area per capita is still relatively low, Therefore, it can be seen as a representative and typical case for understanding more about people's use of green space in major Chinese cities.

The research team sampled survey respondents using the probability proportionate to population size (PPS) sampling method. In the first stage, 26 urban residential neighbourhoods (*she qu*, a small-scale administrative unit in Chinese cities) were chosen randomly from seven districts in Guangzhou (Fig S1). In the second stage, 39 households from each of the targeted neighbourhoods were randomly chosen and visited by the research team, and one person from each household was randomly selected, based on the Kish Grid method (Oldendick et al., 1988), which involves using a pre-assigned table of random numbers to select an individual. In total, 1003 respondents were recruited. After excluding participants with missing information for any of the variables (dependent variables, independent variables and confounders), the final dataset used in this study yielded a total of 990 samples. The age structure of the full sample is presented in Table S1, and the results of the comparison between participants' demographics and city-level census information (Table S2) suggested that this survey data is representative of Guangzhou as a whole.

2.2. Dependent variables

We evaluated self-reported neighbourhood GS usage and perceived comfort of neighbourhood GS (a proxy for the perception of GS as satisfactory) via two questions. Firstly, respondents were asked: ''Please evaluate how frequently you have used the GSs in this neighbourhood in the past six months''. Responses to the statement ranged from "1=never'' to ''5=always''. Following existing studies (Bloemsma et al., 2018; J. Schipperijn et al., 2010, 2010b), the responses were then dichotomised as low frequency (1 = ''1'' and ''2'') and high frequency (0 = ''3'' ''4'' and ''5''). Secondly, respondents were asked: ''Do you agree that you feel comfortable in open space such as GSs, parks, and square in this neighbourhood?''. The response options ranged from ''1=strongly disagree'' to ''5=strongly agree''. Responses to this question were similarly dichotomised as ''low perceived comfort'' (1 = ''1'' and ''2'') and 'high perceived comfort' (0 = ''3'' ''4'' and ''5'').

2.3. Independent variables

As this study aims to compare the conditional effect of two types of GS availability (overall vs. eye-level), we used the Normalised Difference Vegetation Index (NDVI) and Street View Greenness (SVG) as metrics of GS availability. Park proximity was also included to control for the effect of major green infrastructure. NDVI and park proximity are usually assessed based on remote sensing data and land use data, which can be used to reflect the availability and accessibility of GS (Nordbø et al., 2018), respectively. SVG, by contrast, is normally used for measuring eye-level GS exposure because it is collected at street level, and can therefore reflect the presence of small and visible on-street vegetation (Wang et al., 2024).

2.3.1. NDVI

The NDVI (Tucker, 1979) was calculated using satellite images from Landsat8 in 30 m spatial resolution, taken in 2016. Based on existing studies (Markevych et al., 2017), and to avoid including bodies of water resulting from pixels with negative values when calculating NDVI values within a neighbourhood, any negative values were disregarded. The NDVI was calculated using all the cells with positive values within 1000-metre Euclidean buffers for each neighbourhood. We used the 1000-metre buffers because they typically equate to a 10 to 15-minute walking distance, thus capturing most people's daily scope of activities within neighbourhoods (Merriam et al., 2017). We also calculated the Soil Adjusted Vegetation Index (SAVI) (Huete, 1988). However, we did not include it in the main models because it was highly correlated with NDVI ($r > 0.90$, $p < 0.001$).

2.3.2. SVG

SVG was calculated using Tencent street view images taken in 2016. We downloaded Tencent Street View images with an application programming interface (API), following previous studies (Wang et al., 2021a–c). We established sampling points from which to collect street-view images based on OpenStreetMap (Haklay and Weber, 2008). For each sampling point, we collected four street view images taken from different angles (0, 90, 180, and 270°). In total, we created 41,286 sampling points within the research area.

Following Wang et al. (2021a–c), we used the fully convolutional network with an output stride of 8 (FCN-8 s) architecture to carry out the semantic image segmentation. This has the ability to identify >150 kinds of objects (e.g. GS elements such as trees and grass) accurately (Long et al. 2015). The training data used was the ADE20 K semantic segmentation data set (Zhou et al., 2019). An example of image segmentation using the FCN-8 s is provided in the supplementary file (Fig, S2). The SVG per sampling point was measured as the proportion of pixels representing GS in the four street view images, in line with previous studies (Wang et al., 2021a–c). We calculated the SVG for each neighbourhood by averaging the SVG scores for all the sampling points within the 1000-metre circular buffers.

2.3.3. Park proximity

Following existing studies (Li et al., 2020), the location of urban parks was based on the 2016 Autonavi electronic navigation map, which offers the most comprehensive and geographical information about different facilities. Park proximity was measured by the distance to the nearest park (straight-line distance in metres from the centroid of a neighbourhood to the edge of the nearest park).

2.3.4. Perceived safety

Perceived safety was measured by a single self-reported question. Respondents' perceptions of how safe they felt in the neighbourhood were assessed using the following question: ''How satisfied are you with the neighbourhood security conditions?'' (answers ranged from 1 = ''very dissatisfied'' to 5 = ''very satisfied''). Following existing studies (Choi and Matz-Costa, 2018; Foster et al., 2004; Kwarteng et al., 2018; Lovasi et al., 2014; Piro et al., 2006), the responses were dichotomised as 'high levels of safety' (''4'' and ''5'') and ''low levels of safety'' (''1'', ''2'' and ''3''); the latter was used as a reference group in the analysis.

2.4. Confounders

We adjusted the modelling for a series of individual confounders based on the survey data, including gender, age (years), highest educational attainment, marital status, hukou status (a household registration system which determines whether residents are permitted full access to public services at a low cost or not), and average annual household income per household member. In addition, physical health (with chronic diseases vs. without chronic diseases), mental health (The World Health Organisation-Five Well-Being Index) (Topp et al., 2015) and duration of residence (years) were included. Following previous studies (Campagnaro et al., 2020; Fermino et al., 2013; Fisher et al., 2021; Fongar et al., 2019; Groshong et al., 2020; Hong et al., 2018; Jansson et al., 2013; Li et al., 2015; Mouratidis, 2019; Sang et al., 2016; Tzoulas and James, 2010), several built environment covariates were considered, namely: neighbourhood-level population density (persons/km^2), neighbourhood-level street intersection connectivity (number of interactions/km^2), and neighbourhood-level land use mix (assessed by the entropy of different types of points of interest). These built environment covariates were retrieved from the census and Tencent Maps (Li et al., 2022).

2.5. Statistical analysis

To understand more about the relationship between neighbourhood GS availability, and the use and perceived comfort of GS, we used multilevel linear and logistic regressions (Stephen W Raudenbush and Bryk, 2002), because individuals in this study were nested in neighbourhoods which means that our data was hierarchical in structure. The calculation of variance inflation factors (VIF<3) indicated that there were no serious multicollinearity issues for all the variables. The intra-class correlation coefficients (ICC) for the null model, predicting the use of GS, were 0.249 (linear regression model) and 0.488 (logistic regression model), respectively; and the ICCs for the null model, predicting the perceived comfort of GS, were 0.246 (linear regression model) and 0.385 (logistic regression model), respectively. This means that neighbourhood-level variance accounted for >20 % of the total variance in respondents' use of and perceived comfort of GS.

To compare how the effects varied between the different predictors, we regressed the use of GS and perceived comfort of GS for the GS indicators respectively. First, we ran the baseline models which included all the independent variables and covariates. Model 1 and Model 2 predicted the use of GS, which was treated as a continuous variable and binary variables, respectively. The outcomes were further tested as continuous variables because dichotomising them as binary variables may have risked neglecting the potential differences between various responses. Additional analyses of this type can be used to test the robustness of the results. Model 3 and Model 4 were used to predict the perceived comfort of GS, which was treated as a continuous variable and a binary variable, respectively. Second, additional analyses were conducted based on stratification of the respondents' perceptions of neighbourhood safety (high neighbourhood safety vs. low neighbourhood safety) to predict the use of GS (Model 5 to Model 8) and the perceived comfort of GS (Model 9 to Model 12). An interaction term for the full model, between GS and perceived safety, was incorporated into the linear regression models. In the logistic regression models, we estimated the relative excess risk due to interaction (RERI) to reflect the interaction term. The significance level of the interaction terms was then assessed to identify whether the effect of the GS indicators varies significantly between the high-neighbourhood safety and low-neighbourhood safety groups.

We conducted several sensitivity analyses. First, we re-coded 'low frequency' (1 = ''1'', ''2'' and ''3''), and ''high frequency'' (0 = ''4'' and ''5'') use of GS, and ''low perceived comfort'' (1 = ''1'', ''2'' and ''3'') and ''high perceived comfort'' (0 = ''4'' and ''5'') of GS (Table S3). The results remained similar, so we decided to use the former coding strategy for the two dependent variables. Second, we also used 800-m and 1500-m buffers in the additional sensitivity analysis (Fig S3). As existing studies suggested that people's use and perceptions of GS may vary according to age and gender (Sang et al., 2016), we further stratified our analysis by gender (Fig S4) and age (Fig S5) in the sensitivity analysis. The results indicated that, despite some differences in the value of the coefficient, the associations between GS availability and the use/ perceived comfort of GS remained the same. Therefore, we decided to retain the 1000-m buffer and did not stratify the analysis by age and gender in our main models. Lastly, we tested whether the use of GS mediates the association between GS availability and the perceived comfort of GS using multilevel structural equation models (SEM) (Rabe-Hesketh et al., 2004) (Fig S6). The results suggested that there is no evidence that the use of GS plays a mediating role based on the Sobel tests (Sobel, 1982), so we decided not to use SEM.

3. Results

3.1. Characteristics of key variables

Table 1 summarises the descriptive statistics of the participants. Approximately 80 % of the respondents perceived their neighbourhoods to be very safe, while nearly 74 % frequently used GSs, and 77 % had a high level of perceived comfort with the GSs available to them. The median NDVI and SVG values for their neighbourhoods were 0.104 and 0.191, respectively. The results of the correlation analysis between the dependent and independent variables are presented in Table S4.

3.2. Baseline models

Fig. 1a and c show the associations between the NDVI, SVG, distance to the nearest park and the frequency of using GS (the full results of the adjusted models are provided in Table S5). The results indicate that the SVG was positively related to the frequency of using GS (Model 1. SVG: Coef = 0.535, 95 % CI = 0.110,0.960). However, there is no evidence that NDVI (Model 1. NDVI: Coef = −0.017, 95 % CI = −0.549,0.514) or distance to the nearest park (Model 1. Park: Coef = −0.001, 95 % CI = −0.001,0.000) was related to the frequency of using GS. Both the NDVI and SVG were negatively related to the likelihood of using GS relatively infrequently (Model 2. NDVI: OR = 0.130, 95 % CI = 0.026,0.636; SVG: OR = 0.284, 95 % CI = 0.090,0.898), while there is no evidence that the distance to the nearest park was related to that (Model 2. Park: OR = 1.001, 95 % CI = 0.998,1.002).

Fig. 1b and d show the associations between the NDVI, SVG, distance to the nearest park and perceived comfort of GS (the full results of the adjusted models are provided in Table S6). The results suggest that only distance to the nearest park was negatively related to the perceived comfort of GSs (Model 3. Park: Coef = −0.001, 95 % CI = −0.001,−0.000), and there is no evidence that the NDVI (Model 3. NDVI: Coef = −0.311, 95 % CI = −0.746,0.124) or SVG (Model 3. SVG: Coef = 0.315, 95 % CI = −0.036,0.667) was associated with residents' levels of perceived comfort of GSs. In addition, no evidence was found that either of the GS indicators were related to the odds of individuals having low levels of perceived comfort of GSs (Model 4. NDVI: OR = 1.090, 95 % CI = 0.205,5.785; SVG: OR = 0.506, 95 % CI = 0.132,1.937; Park: OR = 1.001, 95 % CI = 0.999,1.003).

Table 1
Descriptive statistics of participants.

Variables	Mean (Standard Deviation)/ Proportion
Dependent variables	
Frequency of using GS (1–5)	3.113 (1.001)
High (%)	73.636
Low (%)	26.364
Perceived comfort of GS (1–5)	3.122 (0.853)
High (%)	77.071
Low (%)	22.929
Independent variables	
NDVI median (IQR)	0.104 (0.041)
SVG median (IQR)	0.191 (0.082)
Distance to the nearest park (m)	660.260 (40.360)
Perceived safety (%)	
High	80.808
Low	19.192
Covariates	
Gender (%)	
Male	49.899
Female	50.101
Age	36.420 (9.685)
Marital status (%)	
Single, divorced, or widowed	20
Married	80.000
Education (%)	
Primary school or below	6.464
Secondary school	27.071
University and above	66.465
Annual household income per household member (CNY)	15,676.766 (8521.058)
Physical health (%)	
With chronic diseases	12.828
Without chronic diseases	87.172
Mental health (WHO-5)	15.260(3.613)
Duration of residency (years)	13.556 (9.397)
Hukou status (%)	
Local hukou	81.010
Non-local hukou	18.99
Neighbourhood population density (persons/ km^2)	46,809.682 (30,454.199)
Street intersection connectivity (number of interactions/km^2)	284.186 (208.597)
Index of land use mix (0–1)	0.131 (0.024)

3.3. Stratified analysis

Fig 2a and 2c display the associations between the NDVI, SVG, distance to the nearest park and the frequency of using GSs, stratified by respondents' perceptions of safety (high vs. low). While SVG was found to be positively related to the frequency of using GS in the case of residents who perceived a higher level of safety (Model 5. SVG: Coef = 0.461, 95 % CI = 0.010,0.912), it was not significantly related to the frequency of using GS in the case of those residents who perceived the lower level of safety to be lower (Model 6). Neither NDVI nor distance to the nearest park was associated with the frequency of using GS for respondents who perceived either higher or lower levels of safety. Furthermore, although SVG was negatively associated with the odds of using GS relatively infrequently in the case of respondents who perceived a higher level of safety (Model 7. SVG: OR = 0.323, 95 % CI = 0.089,0.77), it was not related to the odds of using GS less frequently in

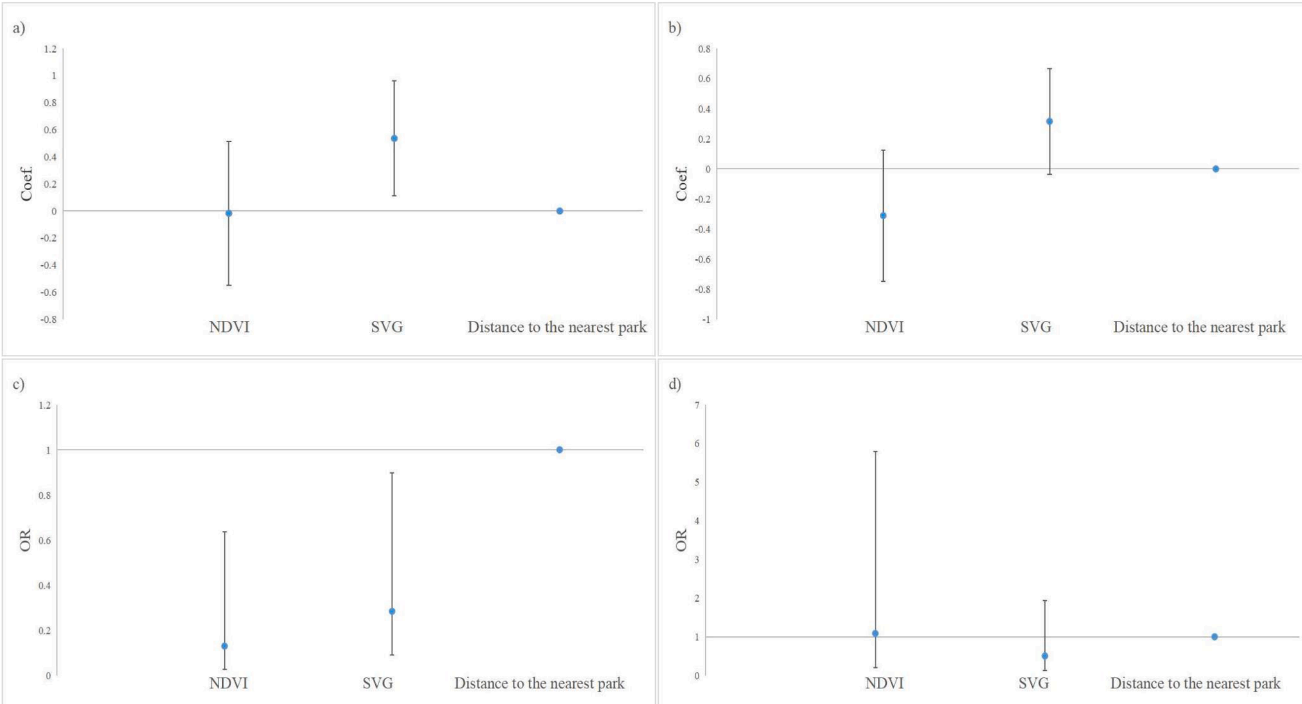

Fig. 1. Associations between the availability of GS and use of GS/perceived comfort of GS: a) use of GS (model 1: continuous variable); b) perceived comfort of GS (model 3: continuous variable); c) use of GS (model 2: binary variable); d) perceived comfort of GS (model 4: binary variable). Note: *p < 0.10, **p < 0.05, ***p < 0.01.

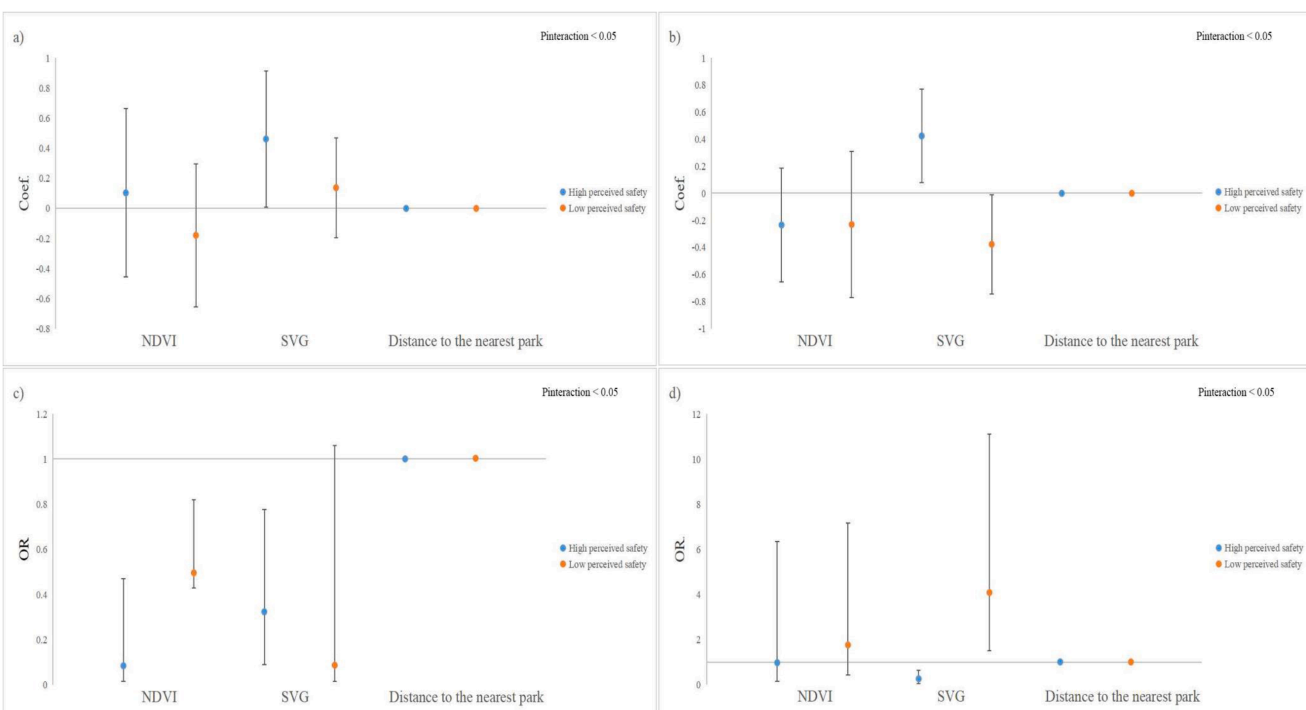

Fig. 2. Associations between availability of GS and use of GS/perceived comfort of GS. Results are presented with stratification for perceptions of safety as high or low: a) use of GS (model 5 and 6: continuous variable); b) perceived comfort of GS (model 9 and 10: continuous variable); c) use of GS (model 7 and 8: binary variable); d) perceived comfort of GS (model 11 and 12: binary variable). Note: Models adjusted for all covariates. An interaction term for the full model, between GS and perceived safety, was incorporated into the linear regression models. In the logistic regression models, we estimated the relative excess risk due to interaction (RERI) to reflect the interaction term.*p < 0.10, **p < 0.05, ***p < 0.01.

the case of respondents who perceived a lower level of safety. However, the NDVI was negatively associated with the likelihood of using GS infrequently in the case of both those respondents who perceived a higher level of safety or a lower level of safety (Model 7. NDVI: OR = 0.084, 95 % CI = 0.015,0.470; NDVI: Model 8. OR = 0.496, 95 % CI = 0.430,0.819). Lastly, although distance to the nearest park was not related to the odds of using GS infrequently in the case of respondents who perceived a higher level of safety, it was positively associated with the odds of using GS infrequently for respondents who perceived a lower level of safety (Model 7. Distance to the nearest park: OR = 1.003, 95 % CI = 1.001,1.006).

Fig 2b and 2d display the associations between NDVI, SVG, distance to the nearest park and perceived comfort of GSs, stratified by perceived safety levels. While SVG was positively related to the perceived comfort of GSs for those residents who perceived a higher level of safety (Model 9. SVG: Coef = 0.423, 95 % CI = 0.079,0.768), it was negatively related to the perceived comfort of GSs for those who perceived a lower level of safety (Model 10. SVG: Coef = −0.377, 95 % CI = −0.744,−0.010). There was no evidence that NDVI is related to the perceived comfort of GSs in the case of respondents who perceived a lower level of safety. In addition, distance to the nearest park was negatively related to the perceived comfort of GSs both for those respondents who perceived a higher level or a lower level of safety (Model 9. Distance to the nearest park: Coef = −0.001, 95 % CI = −0.001, −0.000; Distance to the nearest park: Model 10. Coef = −0.001, 95 % CI = −0.001,−0.000). Furthermore, although SVG was negatively related to the perceived comfort of GSs for those residents who perceived a higher level of safety (Model 10. OR = 0.253, 95 % CI = 0.052,0.633), it was positively linked to the odds of being dissatisfied with GSs for their counterparts who perceived a lower level of safety (Model 12. OR = 4.079, 95 % CI = 1.499–11.100). However, neither NDVI nor distance to the nearest park was related to the odds of being dissatisfied with GSs for those respondents who perceived either a higher or a lower level of safety

4. Discussion

By exploring how perceived safety moderates the associations between neighbourhood GS availability and residents' use of and perceived comfort of GS, using survey data collected in Guangzhou, we yielded two major findings.

This study is the first to confirm that SVG is positively associated with both the use of GS and the perceived comfort of GS. Eye-level greenness was positively related to the use of and perceived comfort of GS for those respondents with a higher level of perceived neighbourhood safety; it was also negatively related to the use and perceived comfort of GS in the case of respondents with a lower level of perceived neighbourhood safety. There are two explanations for these findings. First, when people feel that a neighbourhood is unsafe, they are more likely to perceive GS as a potentially dangerous area where crimes might take place (Bogar and Beyer, 2016; Fleming et al., 2016). Consequently, they may be less inclined to frequent places with high levels of SVG, the indicator that captures the amount of perceived GS at eye level. Hence, the underlying pathways (e.g. engaging in physical activity and social contact) linking the availability and the use of GS may not operate in the same way if the GS in the neighbourhood is perceived as unsafe, because people may feel nervous about using it (Campagnaro et al., 2020; Tzoulas and James, 2010). Second, perceived safety is an important factor which influences people's preferences for GS (Yakinlar and Akpinar, 2022). One of the most important motivations for people to use GS is that it can help reduce stress and improve concentration and mental functioning (Stoltz and Grahn, 2021). A prerequisite for the restorative quality of GS is that one must be able to appreciate and relax within the environment (Grahn and Stigsdotter, 2010). However, if they feel unsafe in the environment, this may prevent people from fully appreciating the landscape and being able to relax (Bogar and Beyer, 2016; Fleming et al., 2016). Previous studies have also found that, when people feel unsafe in the environment, they are more likely to associate GS with negative emotions, which explains the negative association between greenness and the use of and perceived comfort of GS (Jansson et al., 2013; Mouratidis, 2019; Wu et al., 2019).

The study found that NDVI was positively related to the use of GS, while park accessibility was related to people's levels of perceived comfort with GS. Evidence from previous studies regarding the relationship between NDVI and the use of GS is mixed. Some studies have found that NDVI was positively related to the use of GS (van den Berg et al., 2017), while others have claimed that there is no association between the two (Bloemsma et al., 2018). Existing studies have also demonstrated that there is a dose-response effect association between the availability of GS and its restorative qualities (Jiang et al., 2014), which means that the effect of GS will only be significant when it reaches a certain level, but its effect may decrease when the level is too high. The NDVI value in our study (0.12 at the median) and in van den Berg et al.'s (2017) study (0.38 at the median) is smaller than that obtained by Bloemsma et al.'s (2018) (0.58 at the median, which may be too high to attract visitors). In addition, the level of NDVI in this study may not be high enough to be significantly related to the perceived comfort of GS, while park accessibility may also not be high enough to be significantly related to the use of GS. Therefore, one possible explanation for the inconsistent findings is that they could be due to the varying levels of NDVI and park accessibility in different studies.

We further found that NDVI was positively associated with the use of GS, while park accessibility was positively related to the perceived comfort of GS regardless of the level of perceived neighbourhood safety, which means that perceived safety may not be a potential prerequisite for the relationship between the overall availability of GS and the use of GS. This is consistent with the finding from Juul and Nordbø's (2023) study, which also found that perceived safety had no moderating effect on NDVI. However, some other studies found that perceived safety did have a moderating effect on park accessibility (Hong et al., 2018) and perceived GS (Weimann et al., 2017). There are two possible explanations for this. First, before a link between perceived safety levels and the availability of GS (greenness) to the motivation for using GS can be established, people must be able to perceive and view the GS (Li et al., 2015). Prior literature has found that NDVI and park accessibility differs from SVG in that it is unable to accurately reflect perceived GS from a pedestrian's perspective (Wang et al., 2021a–c). Therefore, perceived safety does not influence the relationship between the overall availability of GS and the use of GS according to this study, because the overall availability of GS may not be an accurate reflection of how people view and perceive the GS at the ground level which may be more influenced by pedestrians' perceptions. Second, the overall amount of GS, as measured by the overall availability of GS from an overhead perspective, primarily consists of large green areas that form part of the infrastructure, such as parks, which are often well-managed and well-maintained within our study area (Ye et al., 2019). The perceived safety variable may only reflect people's perceptions of the GS around them, which may not provide a very reliable indication of the perceived safety of large GSs that form part of the infrastructure (Weimann et al., 2017). Therefore, the relationship between the overall availability of GS and the use of GS was not modified by respondents' perceptions of safety in this study.

4.1. Policy implications

Assessing the associations between perceived safety, GS availability, use, and perceived comfort of GS has several potential policy implications. First, this study indicated that improving the overall availability of GS may be positively linked to the use of GS, so policymakers could consider either creating more green infrastructure (e.g. public parks) or improving the accessibility of existing green infrastructure (e.g. improving the street network and public transportation around parks). However, because there is a dose-response effect association between the availability of GS and its restorative qualities (Jiang et al., 2014), any changes to the green infrastructure should be monitored to ensure that GS is at an optimal level to benefit residents. Second, as the positive effect of GS on the use of GS is more pronounced in a safe environment, policymakers need to improve neighbourhood safety in order to maximise the benefits of GS. For example, they could add more safety-related facilities such as CCTVs and street lights to GSs and the surrounding areas.

4.2. Strengths and limitations

This study has the following notable strengths. First, previous studies have often overlooked street-level GS due to methodological limitations, which may partially explain their inconsistent findings. For example, some street vegetation is too small to be detected by satellite imagery, so NDVI may underestimate people's daily exposure to street greenery. This study used both overhead-view GS (NDVI) and eye-level GS (SVG), and in doing so it provided a possible explanation for the inconsistent findings produced by previous studies. Second, this study focused on both the use of and perceived comfort of GS, which meant that it was able to offer more useful insights regarding the management of GS. Third, the study focused on a high-density urban area in China, thus enhancing our understanding of the use of GS in developing countries.

There are also some limitations to be noted. First, this research used cross-sectional survey data, so it may not be possible to infer causality. For example, we cannot fully eliminate residential self-selection bias, because we could not control for some unobserved personal attributes which may have influenced both respondents' use of GS and their preferences for living in greener neighbourhoods. Future studies should consider using a natural experiment study design (He et al., 2022). It should also be borne in mind that the data was collected in 2016, so the results may not be fully valid regarding the current context in the research area. Second, in this study, safety was self-reported, because there was no measure of objective safety (e.g. crime rates) available. However, it may be necessary to use an objective measure of neighbourhood safety to improve the accuracy of the results (Stephen W. Raudenbush and Sampson, 1999). Additionally, we did not include GS characteristics associated with safety such as the presence of CCTVs or street lights, which may lead to bias in our estimation. Third, this study was also affected by the Modifiable Area Unit Problem (MAUP) (Fotheringham and Wong, 1991), as only a single circular buffer was used to define the scope of each neighbourhood. It would therefore be worth considering using multiple buffers of different sizes or different ways of defining them (e.g. street network buffers or weighting with distance decay) in future studies. Fourth, although most plants in our research area are evergreen or semi-evergreen, the GS indicators may still not be able to fully reflect seasonal variances in local vegetation, which could lead to bias in our estimation. Fifth, although perceived safety, and the use and perceived comfort of green space are ordinal variables, we converted them to binary variables in order to simplify the analysis. However, this may lead to bias because dichotomising the responses could neglect the potential differences between them. Lastly, we may have neglected the spatial autocorrelation of green infrastructure which may influence people's use of green space.

5. Conclusion

This study is one of the first to systematically examine how perceived levels of safety moderate the associations between GS availability, the use of GS and the perceived comfort of GS in a densely populated urban context in China. We used NDVI, park accessibility and SVG to assess two types of GS availability. Our results suggest that perceived safety may be a potential prerequisite for the relationship between eye-level neighbourhood GS and the use of and perceived comfort of GS, but not for the relationship between the overall availability of neighbourhood GS and the use of and perceived comfort of GS. To achieve the goal of encouraging people to use GS, residents' perceptions of safety should be considered in the planning process. The heterogeneous effects of both eye-level GS and the overall amount of GS should also be considered before implementing any interventions to promote the use of and perceived comfort of GS.

Statement of ethical approval

The study was granted ethical approval and authorised by the Sun Yat-Sen University Research Ethics Committee. All the participants were informed and consented to the study protocol.

Ethical approval

The survey was consented by the Sun Yat-Sen University Research Ethics Committee. All the subjects were informed and consented to the protocol of study.

CRediT authorship contribution statement

Ruoyu Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Yuxiao Jiang:** Methodology. **Dongwei Liu:** Methodology. **Huiwen Peng:** Writing – review & editing. **Mengqiu Cao:** Writing – review & editing, Supervision. **Yao Yao:** Methodology.

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.

Acknowledgements

The research is funded by the National Natural Science Foundation of China (41801306, 42471491). The authors would also like to thank Professor Suhong Zhou and her research team for providing us with the survey data. The survey was consented by the Sun Yat-Sen University Research Ethics Committee. All the subjects were informed and consented to the protocol of study. Finally, thanks also to the editor and the anonymous reviewers for their valuable comments on the initial draft of this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.wss.2025.100247.

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