Journal of Transport & Health 38 (2024) 101834

Contents lists available at ScienceDirect

Journal of Transport & Health

journal homepage: www.elsevier.com/locate/jth

Using the hierarchy of active travel needs to examine associations between streetscape environments and older adults' active travel in China

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ARTICLE INFO

Keywords:
Age-friendliness
Streetscape built environments
Older adults
Active travel
China

ABSTRACT

Background: Little is known about the extent to which the age-friendliness of streetscape built environments may influence older adults' active travel (AT) patterns. Moreover, with the exception of street greenery, the non-linear and threshold effects of other characteristics of streetscape built environments have not been examined.

Methods: This study used data from the Third Guangzhou Official Household Travel Survey 2017 and Tencent Street View images. Using the Hurdle model and Generalized Additive Mixed Models (GAMMs), we examined the non-linear relationships between streetscape built environments and older adults' AT patterns (i.e., frequency and duration). The models controlled for neighbourhood-level built environment attributes and individual-level characteristics.

Results: Pavement ratio and street obstacles had negative impacts on older adults' AT duration within a certain range, but outside this range, the negative associations no longer held. Street safety, greenery, and vitality were positively associated with older adults' AT duration within a certain range. Street design exerted positive effects on the likelihood of AT. Age-friendly streetscape built environment attributes showed stronger relationships with the likelihood of AT among older adults aged 70–79, and larger impacts on AT duration for older adults aged 60–69. Notably, street greenery had positive impacts on both AT frequency and duration among older adults aged 80 and above.

Conclusions: The results showed significant non-linear associations between six streetscape built environment characteristics and older adults' AT patterns. This study provides implications for building age-friendly streetscape built environments.

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https://doi.org/10.1016/j.jth.2024.101834
Received 4 September 2023; Received in revised form 11 April 2024; Accepted 22 May 2024
Available online 24 June 2024

1. Introduction

Being sufficiently physical active is essential for better ageing. Older adults' physical activities have been shown to contribute to a wide range of health benefits, such as reduced morbidity, enhanced functional ability, and improved psychological wellbeing (World Health Organization, 2022). In fact, an estimated 31% of the world's population suffers from insufficient levels of physical activities, especially the older-adult population (Hallal et al., 2012). Older adults on average spent more than 9.4 hours in sedentary activities per day (Harvey et al., 2015). For older adults, physical inactivity leads to health problems, obesity, non-communicable diseases, and chronic conditions. To reduce these health issues, the World Health Organization (WHO) has called for attention to the creation of age-friendly built environments that encourage older adults' active travel (hereafter AT) as part of its Healthy Ageing initiative (World Health Organization, 2015).

AT is one of the daily physical activities for older adults, including walking and cycling. Encouraging AT is an efficacious way to increase older adults' daily physical activities (Hallal et al., 2012; Morency et al., 2011). AT has been documented to significantly preserve functional abilities and reduce the risk of chronic diseases among older adults (Diehr and Hirsch, 2010). Older adults' AT distance is around 0.5 km∼2 km from their residences (Prins et al., 2014; Tsunoda et al., 2021), and travel duration is 20 minutes on average (O'Hern and Oxley, 2015; Yang et al., 2018, 2022). The trip purposes of AT consist of destination visits, strolling, and other purposes (Perchoux et al., 2019).

Since aging concurs with decreased physical capacities, engagement in AT may vary among different age cohorts of older adults (i.e., young-old, middle-old, and old-old). Compared to young adults, older adults have been reported to make fewer daily transport trips and travel shorter distances (Figueroa et al., 2014). However, research shows inconsistent findings on the changes in older adults' participation in AT. Yang et al.'s (2018) study in the US found a decreasing amount of AT from young-old to old-old older adults. By contrast, Mertens et al.'s (2019) longitudinal study in Belgium found no significant decrease in older adults' participation in AT over a three-year time period. These inconsistent findings call for more studies on the nature and determinants of older adults' AT.

The built environment has been increasingly acknowledged as a significant determinant in encouraging older adults' AT. The '5D' Elements of the Built Environment model proposes that density, diversity, design, destination accessibility, and distance to public transits are key elements of the built environment that can predict individuals' AT (Ewing and Cervero, 2010). Applying this model to explain older adults' AT, scholars have found that population density (Moniruzzaman et al., 2013), land use mix (Böcker et al., 2017), access to recreational amenities (Cheng et al., 2019; Leung et al., 2018), and distance to public transits (Cheng et al., 2019), were positively associated with older adults' walking behaviours. Nevertheless, this model has focused on built environment elements but ignored older adults' individual conditions, such as age and physical capacity, which contribute to the feasibility of an AT trip.

Alfonzo's Hierarchy of Walking Needs emphasizes the impacts of both individuals and built environments in predicting adults' walking behaviours (Alfonzo, 2005). It consists of five levels of needs: feasibility, accessibility, safety, comfort, and pleasurability. Feasibility refers to the viability of a walking trip, and it accentuates the individual limits (e.g. physical capacities, time) affecting the walking decision-making process. Accessibility, safety, comfort and pleasurability indicate built environment attributes that influence an individual's decision to walk. Specifically, accessibility signifies the convenience of conducting destination or strolling walk trips. Safety refers to the need to feel safe to walk. Comfort emphasizes an individual's level of ease and contentment when walking. Pleasurability focuses on the level of attractiveness of the built environment in regard to an individual's walking experience. Guided by this framework, Alfonzo et al. (2008) found that accessibility and safety were associated with the amount of walking that adult parents conducted inside and around their neighbourhoods in California. However, Alfonzo's empirical research failed to capture the importance of pleasurability using the urban design audit method.

Although Alfonzo's model does allude to the variances of walking determinants among persons from different age groups, it fails to adequately address older adults' walking and cycling needs. For one thing, older adults have been found to prefer obstacle-free and safe built environments for independent AT, since their functional abilities gradually decline (Van Cauwenberg et al., 2018, 2019). For

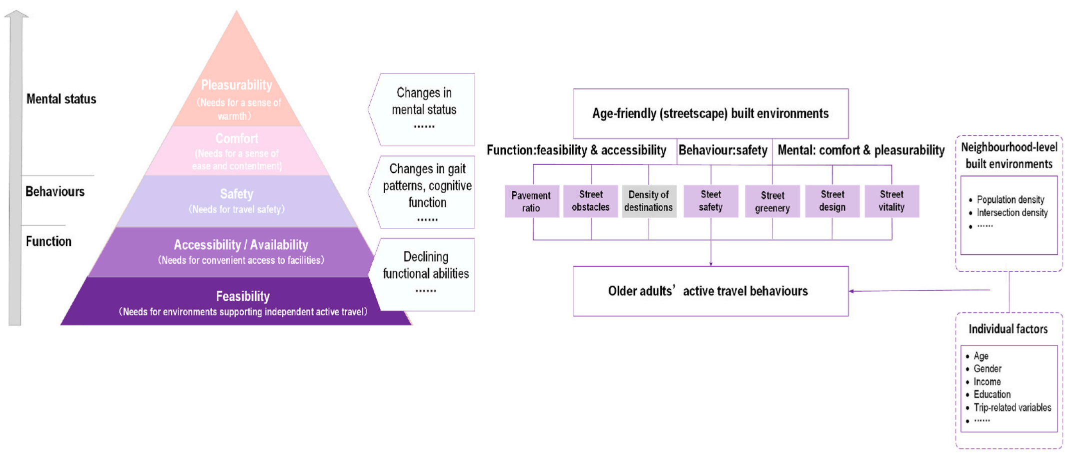


Fig. 1. Theoretical framework of age-friendly streetscape built environments and older adults' active travel behaviours.

another, older adults have been documented to conduct more AT in built environments with open space for recreation and other recreational facilities (Li et al., 2005). Apart from the above-mentioned limitations, Alfozon's model makes no attempt to point out there could be non-linear relationships between built environment attributes and older adults' AT behaviours.

Most empirical studies have examined older adults' AT from the level of accessibility needs (Cheng et al., 2020; Hatamzadeh and Hosseinzadeh, 2020; Yang et al., 2022). Findings show that land use mix (Böcker et al., 2017), access to recreational amenities (Cheng et al., 2019; Leung et al., 2018), and distance to public transits (Cheng et al., 2019) were positively associated with older adults' walking behaviours. As for other levels of needs, two studies have examined the relationship between streetscape greenery and older adults' walking behaviours (Yang et al., 2019, 2021), but without specifying which levels of needs street greenery represents. Overall, with the exception of characteristics representing accessibility needs, built environment attributes that reveal the extent to which other levels of older adults' AT needs are met, have not yet been studied. Moreover, few studies have considered the non-linear relationship between streetscape built environment characteristics and older adults' AT. Yang et al. (2021) found that streetscape greenery had a positive impact on older adults' walking propensity within a certain range. However, other streetscape built environment characteristics were also significant and in need of further investigation of their non-linear and threshold effects. These characteristics are suggested to contribute to older adults' different levels of AT needs and eventually lead to actual AT behaviours.

Based on Alfonzo's Hierarchy of Walking Needs, we developed a theoretical framework named the Hierarchy of Older Adults' Active Travel Needs to measure the age-friendliness of (streetscape) built environments encouraging older adults' AT (Fig. 1). Notably, five dimensions of our framework all focus on revealing the capabilities of (streetscape) built environments in facilitating older adults' independent AT. Older adults' needs for age-friendly (streetscape) built environments supporting AT include *feasibility*, *accessibility/availability*, *safety*, *comfort*, and *pleasurability*. ***Feasibility*** emphasizes the characteristics of streetscape built environments that support independent AT, since older adults experience increasing functional decline. Pavement ratio and street obstacles are two characteristics that reveal the extent to which built environments can support older adults' independent AT. ***Accessibility/availability*** signifies built environment characteristics which make it easier for individuals to conduct destination walking and cycling trips. We used density of destinations to capture this characteristic. ***Safety*** highlights the built environments within which an older adult feels safe to walk and cycle. It caters for older adults' needs for safe AT environments because older adults suffer from slower gait speeds and cognitive decline. We therefore captured the defensible features of built environments, such as street lamps and cameras. ***Comfort*** underlines the quality of built environments which affect the feeling of ease and contentment during AT. We thus assessed the street greenery and street design elements. ***Pleasurability*** emphasizes the enjoyable attributes which make older adults' AT journeys interesting. Thus, we attempted to capture various activities (e.g. social activities, commercial activities) along the built environments where older adults conduct AT.

This study examined the associations between the age-friendliness of (streetscape) built environments and AT patterns (i.e., frequency and duration) among older adults in Guangzhou, China, using data from the Third Guangzhou Official Household Travel Survey 2017 and Tencent Street View images. It contributes to the existing body of knowledge on built environments and older adults' AT from three aspects. First, it extends the existing theories on built environments and older adults' AT by considering older adults' AT needs from their declining physical and mental situation and measuring the age-friendliness of streets using a human-centred approach. Second, it examines the non-linear and threshold effects of six age-friendly streetscape attributes on older adults' AT behaviours for the first time. Third, it considers the influence of age and its interactive association with streetscape environments on older adults' AT behaviours. As for societal significance, this study can provide practical insights for building age-friendly (streetscape) built environments which encourage older adults' AT and thereby contribute to maintaining good functional abilities. Therefore, this research can be beneficial to reducing societal and governmental cost of health problems caused by physical inactivity among older adults.

2. Materials and methods

2.1. Survey design

This study was conducted in Guangzhou, China. As the largest city in Southern China, Guangzhou is experiencing a rapid aging process. In 2023, there are 1.95 million adults aged 60 years old and above and registered with local household registration status in Guangzhou, accounting for 18.86% of the whole population with local household registration status. The proportion of older adults is predicted to be doubled in 2030 (Guangzhou Academy Of Social Science, 2018). Its high percentage of older adults has aggravated the burden on healthcare services, transport systems, housing, and etc. Meanwhile, Guangzhou has launched a series of policies to encourage and enable older adults' AT in recent years. For instance, older adults aged 65 years old and above can enjoy free pass of bus and metro (Guangzhou Municipal Government, 2021). Therefore, research in Guangzhou can offer insights for studies on active travel and healthy ageing in other Asian cities.

We used data from the Third Guangzhou Official Household Travel Survey to capture older adults' AT behaviour. The survey was conducted by the Guangzhou Municipal Transportation Bureau in 11 districts from September 11th to 30th in 2017. Participants in the overall survey were aged 6 years old and above and were members of the randomly sampled households in each district. A total of 82,000 sampled households were selected, with a 1.8% sampling rate. The questionnaire applied travel diaries to document details of each trip (e.g., purpose, travel mode, departure time/location, arrival time/location) taken within 24 hours before the survey day. Travel mode had 19 types, including walking, cycling, motorbike, private cars, bus, and metro. It also covered individual and household characteristics. Since street view data are limited in remote areas of Guangzhou, we narrowed down our research area to inner city areas. We finally selected older adults who were aged 60 and above and resided in one of the seven inner-city districts of

Guangzhou (i.e., *Tianhe*, *Haizhu*, *Yuexiu*, *Liwan*, *Panyu*, *Huangpu*, *Baiyun*) at the time of survey (Fig. 2). In total, after removing the travel records with missing data (N = 23), our sample included 54,464 travel records conducted by 21,897 older-adult participants.

2.2. Measures

2.2.1. Measurement of AT behaviours

We used AT frequency and AT duration within 24 hours before the survey day to represent older adults' AT behaviours. AT frequency was measured using the total number of walking and cycling trips conducted by each participant. AT duration was assessed using the time each participant spent on walking and cycling.

2.2.2. Measurement of age-friendly (streetscape) built environments

We measured (streetscape) built environments around participants' residences with 500 m, 800 m, and 1000 m buffer areas. We selected these buffer sizes for two reasons. First, these buffer area sizes capture the built environments within 5 minutes', 10 minutes', and 15 minutes' walk from older-adult participants' residences, respectively. Most older adults' daily activities occur inside these areas (Tsunoda et al., 2021), and therefore these built environments have significant impacts on influencing older adults' AT. Second, these buffer areas reveal the planning practice on spatial optimization of facilities and amenities within the 15-min pedestrian walking distance life cycle in Chinese cities and have been applied in existing studies (Cheng et al., 2019). The analytical models used in this study were based on built environmental attributes extracted within the 500 m buffers. Results from sensitivity analyses by using different sized buffers (i.e., 800 m and 1000 m buffers) confirmed the robustness of the association between age-friendly streetscape built environment attributes and older adults' AT behaviours (Supplementary Materials: Table S2, Table S3). We calculated six streetscape built environment attributes using street view data from the Tencent Map and fully convolutional neural network techniques.

We firstly created sampling points every 50 m along the street network based on the OpenStreetMap data (https://www.openstreetmap.org). Four street view images from four cardinal direction of each sampling point were obtained by querying the application programming interface of Tencent Map (https://map.qq.com/). In total, there were 458,810 sample points with 1,835,240 street view images. We then used a fully convolutional neural network for semantic image segmentation (FCN-8s), which was based on the ADE20K scene parsing and segmentation database, to identify 151 different street objects (including the category of "unknown objects") in each street view image (Helbich et al., 2019; Yao et al., 2019; Zhou et al., 2017, 2018). The accuracy of the FCN-8s model reached 81.44% in the training set and 66.83% in the test set, which have been verified and applied in previous studies (Dai et al., 2021; Wang et al., 2022a; Wu et al., 2021). We finally calculated the pixel-wise proportion of each street object per street view image, and averaged the values across four images of each sampling point within each buffer.

We evaluated the six age-friendly streetscape built environment attributes based on the value of pixel-wise proportion of each street object. For the ***feasibility*** needs, pavement ratio and street obstacle were assessed. *Pavement ratio* is the ratio of pavement pixels to the total pixels of both pavement and roadway. *Street obstacle* captures the presence of obstacles that may have a negative effect on older

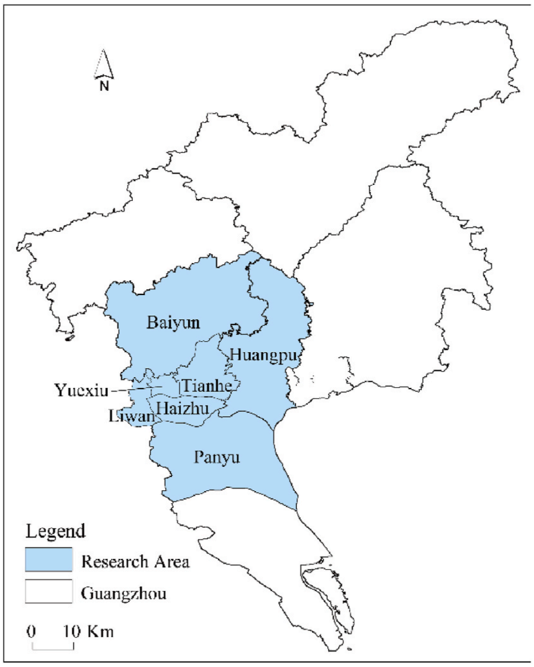


Fig. 2. Research area.

adults' independent AT. We computed this indicator by averaging the total pixel values of fences, railings, stairs, stairways, and steps of all sampling points within a circular buffer. For ***safety*** needs, *street safety* was calculated as the average pixel values of all safety-related street furniture (i.e., streetlamp, light, traffic light, window, and camera). As for ***comfort*** needs, *street greenery* was represented by the average value of the pixels classified as tree, grass, plant, flower, and palm tree of all sampling points within each buffer. For ***pleasurability*** needs, street design and street vitality were measured. We defined *street design* as the average value of the total pixels of street furniture related to aesthetic and leisure (i.e., chair, seat, desk, bench, fountain). ***Street vitality*** was calculated by the average pixel value of the street objects which indicated commercial and pedestrians' activities (i.e., persons, bicycles, booths, trade names and signboards). Formulas for each streetscape attribute were given in the supplementary materials (Table S1).

For *availability* needs, we measured the ***density of facilities*** which supported older adults' daily life within the 500 m buffer area of each participant. The facilities included community centres, educational facilities, hospitals, primary schools, shops, and facilities for physical activities. The number of the above-mentioned facilities within each buffer was calculated based on the point of interest (POI) data.

2.2.3. Measurement of covariates

The study controlled for intersection density, population density, and building density to identify neighbourhood-level characteristics of built environments within the circular buffer. Population data were extracted from WorldPop (https://www.worldpop.org/), and were calculated as the number of persons per hundred square metres. Building density was the ratio of total base area of buildings to the area of the circular buffer. For individual-level covariates, we adjusted for age, sex, educational attainment, annual individual income, *Hukou* status, number of family members, number of bicycles, and number of private cars. Regarding individuals' travel-related covariates, we included the total travel distance and total travel duration of each participant during the 24-h period.

2.3. Statistical analyses

We conducted descriptive analysis to reveal the sample characteristics and the spatial pattern of the age-friendly streetscape built environment attributes. For the spatial analysis, we generated a 500 m × 500 m fishnet with 8277 grids across the research area. The size of a grid is 25 ha, falling within the area of a 10-minute pedestrian distance life circle (MINISTRY OF HOUSING AND URBAN-RURAL DEVELOPMENT OF THE PEOPLE'S REPUBLIC OF CHINA, 2022). A grid is the basic unit of the spatial analysis of the six age-friendly streetscape built environment attributes.

We applied the Hurdle model (Cragg, 1971) to examine associations between (streetscape) built environments and older adults' AT frequency. Since AT frequency in the dataset was a zero-truncated count variable (with 33.31% of participants doing no AT), we used the Hurdle model to examine the relationships between the age-friendly (streetscape) built environment attributes and older adults' AT frequency. Different from the traditional count-data models, such as the Poisson model, the Hurdle model is a two-part decision model.

Table 1
Summary statistics of the sample (N = 21,897).

Characteristics	Proportion/Mean (SD)	Characteristics	Proportion/Mean (SD)
Dependent variables		*Socio-economic status*	
AT frequency	1.57 (1.37)	Educational attainment (%)	
AT duration (min)	29.32 (31.37)	Junior high school or below	57.70
Independent variables		Senior high school	31.68
Streetscape built environment attributes (residence: 500m buffer)		College or above	10.62
Pavement ratio	0.22 (0.13)	Annual individual income (%)	
Street obstacles	0.01 (0.01)	Less than 50,000	75.58
Street safety	0.04 (0.02)	50,000–100,000	20.90
Street greenery	0.22 (0.09)	100,000–200,000	3.18
Street design	0.001 (0.001)	More than 200,000	0.34
Street vitality	0.01 (0.01)		
Built environment attributes (residence: 500m buffer)		Hukou status (%)	
Density of community centres	0.45 (0.94)	Local hukou	95.77
Density of educational facilities	3.81 (9.17)	Non-local hukou	4.23
Density of hospitals, clinics, pharmacies	22.91 (25.28)	Number of family members	2.89 (1.21)
Density of primary schools	4.75 (4.00)	Number of bicycles	0.34 (0.60)
Density of shops, supermarkets, malls	14.42 (12.06)	Number of cars	0.60 (0.94)
Density of physical activity facilities	11.60 (11.43)		
Other built environment attributes (residence: 500m buffer)		*Trip characteristics*	
Intersection density	28.27 (21.67)	Travel distance (m)	3597.24 (1064.44)
Building density	0.24 (0.11)	Travel duration (min)	24.90 (21.75)
Population density (person/100m^2)	261.56 (243.30)		
Covariates			
Demographic characteristics			
Age	66.11 (6.00)		
Sex (%)			
Male	50.84		
Female	49.16		

It is a combination of a logistic model to estimate the likelihood of AT and a zero-truncated count-data model to predict the AT intensity (i.e., the number of AT trips) of older adults who made at least one AT trip. In this study, we used the Hurdle model based on the negative binomial distribution.

Furthermore, we screened out a subset of 14,603 respondents who made at least one AT trip during the 24-h period and calculated their total AT duration. We explored the non-linear relationship between the age-friendly (streetscape) built environment attributes and older adults' total AT duration with Generalized Additive Mixed Models (GAMMs). GAMMs can accommodate a variety type of distribution assumptions and offer a data-driven customized non-linear method for identifying the threshold effects of environmental attributes (Wali et al., 2021). Superior to other machine learning approaches (e.g., Gradient Boosting Decision Tree), GAMMs can model the non-linear effects of streetscape built environment attributes, and account for data with nested structures. We fitted GAMMs with negative binomial variance and a logarithmic link function to model the total AT duration. The coefficients (Coef.) and 95% confidence intervals (95% CI) are reported. Non-linear effects were modelled with thin-plate spines. We applied the effective degrees of freedom (EDF) with the Akaike information criterion (AIC) to quantify the strength of nonlinearity between streetscape built environment attributes and older adults' AT duration. The EDF is a statistical indicator to reflect the degree of nonlinearity of a curve. A statistically significant EDF greater than 1 means a complex non-linear pattern, and a >10-unit AIC decrease provides strong evidence for the non-linear relationship (Lu et al., 2019; Wali et al., 2021; Wang et al., 2022b; Wood, 2006; Yang et al., 2020).

We performed a multi-collinearity test with variance inflation factors (VIF) before conducting the above-mentioned models. Model 1 and Model 2 examined the relationship between the age-friendly streetscape built environment attributes and AT frequency and AT duration with the Hurdle model and GAMMs, respectively. We then conducted stratified analyses based on respondents' age (60–69 years old vs. 70–79 years old vs. older than 80 years) (Model 3 and Model 4). Hurdle models were conducted in STATA 17.0, while GAMMs analyses was conducted in R with the "mgcv" package.

3. Results

3.1. Descriptive statistics

Table 1 summarizes the descriptive statistics of the study variables. Older adults on average conducted 1.57 AT trips and 29.32 minutes of AT during the 24-h period, respectively. As for age-friendly streetscape built environment around the residence, the average values of pavement ratio, street obstacles, street safety, street greenery, street design and street vitality within the 500 m circular buffer were 0.22, 0.01, 0.04, 0.22, 0.001 and 0.01, respectively. For the density of facilities, older adults' residences were characterized by a sufficient number of hospitals, clinics, pharmacies (22.91), shops, supermarkets, malls (14.42), and physical activity facilities (11.60).

The spatial patterns of the age-friendly streetscape built environment attributes are shown in Fig. 3. Pavement ratio (Fig. 3a) and street safety (Fig. 3c) appeared to show a similar spatial pattern. Overall, the pavement ratio and street safety in the central urban areas exhibit higher scores, such as the northern parts of Liwan district and Yuexiu district, the northwest of Haizhu district, and the southern part of Panyu district, while the suburbs have lower scores. Fig. 4showed the high and low value of pavement ratio and street safety in Liwan and Huangpu districts, respectively. Unlike the spatial patterns of pavement ratio and street safety, street greenery showed a

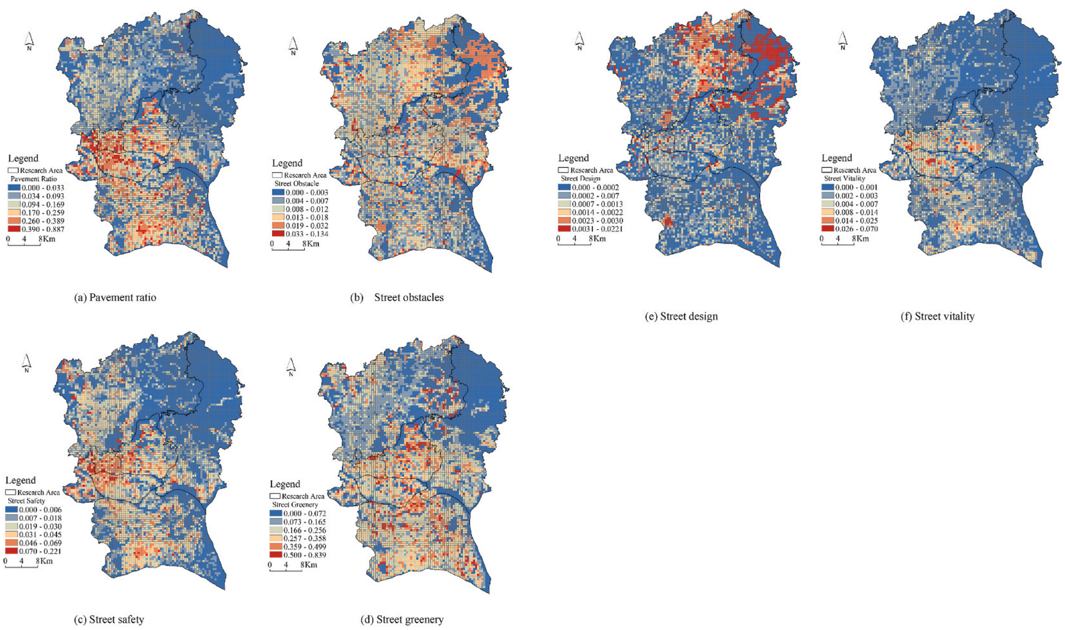
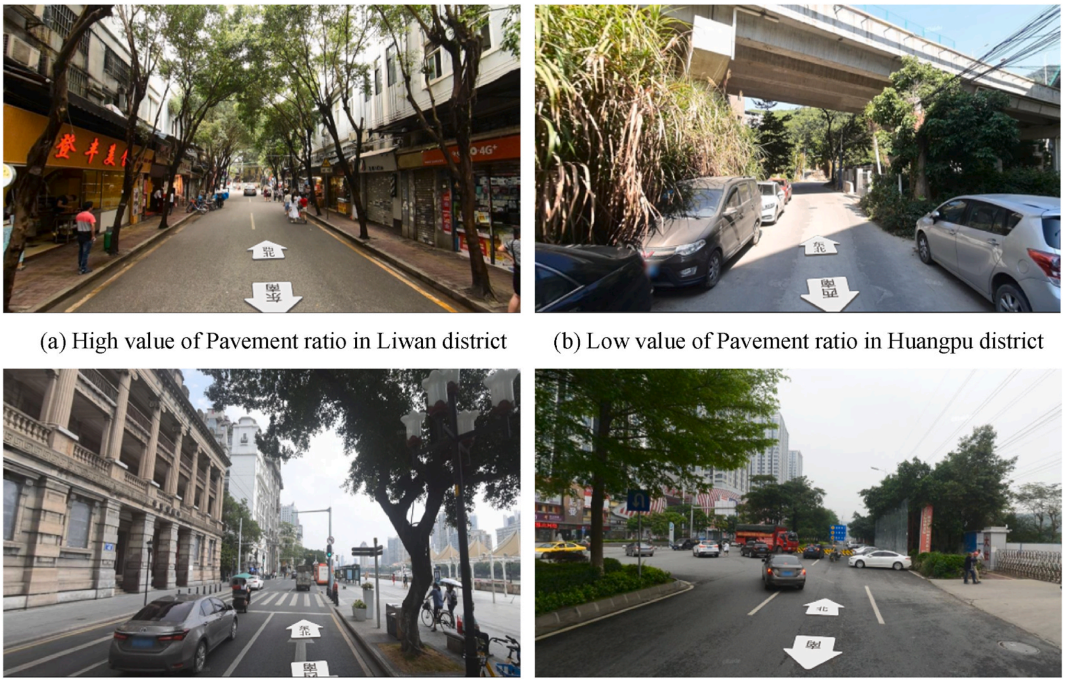


Fig. 3. Spatial distribution of six streetscape attributes in our research area.



(a) High value of Pavement ratio in Liwan district (b) Low value of Pavement ratio in Huangpu district

(c) High value of Street safety in Liwan district (d) Low value of Street safety in Huangpu district

Fig. 4. Differences of pavement ratio and street safety in different districts (The street view images were extracted from the Tencent Map).

slightly dispersed spatial distribution. It showed higher scores in the core areas of central urban districts (e.g., Tianhe, Haizhu, and Yuexiu districts), as well as the eastern part of Panyu, a suburban district of Guangzhou (Fig. 3d). Street vitality appeared to show a more concentrated spatial pattern, with the central parts of inner-city districts (e.g., Tianhe, Haizhu, and Yuexiu districts) obtaining higher scores (Fig. 3f).

According to Fig. 3b, high- and low-value grids of street obstacles were interspersed. The differences in spatial distribution between the central and suburban districts were not as significant as the differences observed in the other streetscape built environment attributes. Finally, the value of street design was lower in the core areas of central urban districts than that in the outer districts, such as the northern part of Tianhe district, the eastern part of Baiyun district, and Huangpu district (Fig. 3e).

3.2. Relationship between the streetscape built environment attributes, AT frequency, and AT duration

3.2.1. AT frequency

In this section, we investigate the factors associated with older adults' AT frequency using Hurdle regression (Table 2, Model 1). Travel distance was removed from the Hurdle regression (Model 1) due to the problem of multi-collinearity. Results indicated a higher likelihood of AT and more AT trips among older adults who resided in areas surrounded by streets with obstacles and a lower level of greenery. Moreover, street design was positively associated with the probability of AT. Unexpectedly, the relationships between the pavement ratio, street safety, street vitality and AT frequency were insignificant. As for density of facilities, older adults may make fewer AT trips when residing in places with more community centres and educational facilities. The density of primary schools was positively associated with the likelihood of older adults' AT, while there was a negative relationship between the density of physical activity facilities around their residences and the likelihood of AT.

For covariates, we found that older adults were less likely to conduct AT as they aged. Male older adults had a lower likelihood of AT and made a smaller number of AT trips than females. Older adults with higher educational attainment, local *Hukou* status, and a higher level of annual individual income tended to have a lower likelihood of AT likelihood and a smaller number of AT trips. Moreover, both the number of family members and the number of bicycles in the household were positively related to AT frequency, while the number of cars in the household was negatively associated with the number of AT trips. For travel-related attributes, when we narrowed down the sample to the older adults conducting at least one AT trip during the 24-h period, travel duration was negatively associated with AT trips.

3.2.2. AT duration

In this section, we model the relationships between age-friendly streetscape built environment attributes and the time expenditure of AT among older adult participants who made at least one AT trip with 24 hours before the survey day (N = 14,603). Results from Model 2 showed that street greenery was positively associated with older adults' AT duration. Curvilinear relationships were observed

Table 2
Results of the relationship between the streetscape built environment attributes and AT frequency (Hurdle model) and AT duration (GAMMs).

	Model 1 (AT frequency)				Model 2 (AT duration)	
	Logit model		Negative binomial model		AT duration	
	Coef.	(S.E.)	Coef.	(S.E.)	Coef.	(91% CI)
Streetscape built environment attributes (residence: 500m buffer)						
Pavement ratio	0.084	(0.066)	0.130	(0.215)	*NA*	
Street obstacles	1.190**	(0.560)	3.647**	(1.796)	*NA*	
Street safety	0.325	(0.414)	0.973	(1.339)	*NA*	
Street greenery	−0.216***	(0.047)	−0.263*	(0.145)	0.213***	(0.052,0.374)
Street design	11.898***	(4.393)	2.494	(13.716)	−6.553	(-21.642,8.536)
Street vitality	0.242	(0.860)	−3.786	(3.011)	*NA*	
Built environment attributes (residence: 500m buffer)						
Density of community centres	0.000	(0.004)	−0.054***	(0.011)	−0.031***	(-0.042,-0.021)
Density of educational facilities	0.000	(0.000)	−0.004***	(0.001)	0.027***	(0.014,0.04)
Density of hospitals, clinics, pharmacies	0.000	(0.000)	0.000	(0.001)	−0.041***	(-0.06,-0.022)
Density of primary schools	0.002**	(0.001)	0.003	(0.004)	0.040***	(0.021,0.06)
Density of shops, supermarkets, malls	0.000	(0.000)	0.000	(0.001)	0.043***	(0.024,0.062)
Density of physical activity facilities	−0.001***	(0.000)	0.002	(0.001)	0.000	(-0.002,0.001)
Other built environment attributes (residence: 500m buffer)						
Intersection density	0.000*	(0.000)	0.001	(0.001)	−0.001	(-0.016,0.013)
Building density	−0.262***	(0.046)	0.014	(0.145)	−0.311***	(-0.466,-0.156)
Population density (person/100m^2)	−0.000***	(0.000)	−0.000**	(0.000)	−0.013*	(-0.027,0)
Demographic characteristics						
Age	−0.001**	(0.000)	0.003**	(0.002)	0.002**	(0,0.003)
Sex (Ref: female)						
Male	−0.010*	(0.006)	−0.231***	(0.019)	0.008	(-0.011,0.026)
Socio-economic status						
Educational attainment (Ref: Junior high or below)						
Senior high school	−0.020***	(0.007)	−0.171***	(0.023)	−0.005	(-0.027,0.017)
College or above	−0.008	(0.011)	−0.256***	(0.036)	−0.038**	(-0.074,-0.002)
Annual individual income (Ref: Less than 50,000 yuan)						
50,000–100,000 yuan	−0.015**	(0.007)	0.021	(0.025)	0.049***	(0.025,0.073)
100,000–200,000 yuan	−0.042**	(0.017)	−0.000	(0.057)	0.053*	(-0.005,0.112)
More than 200,000 yuan	−0.080**	(0.040)	−0.537***	(0.169)	0.089	(-0.133,0.311)
Hukou status (Ref: non-local *hukou*)						
Local *hukou*	−0.014	(0.014)	−0.170***	(0.048)	−0.013	(-0.056,0.031)
Number of family members	0.017***	(0.003)	0.072***	(0.009)	−0.006	(-0.015,0.002)
Number of bicycles	0.033***	(0.005)	0.200***	(0.018)	−0.007	(-0.023,0.009)
Number of cars	0.009	(0.005)	−0.310***	(0.013)	−0.025***	(-0.039,-0.011)
Trip characteristics						
Travel distance					0.153***	(0.145,0.162)
Travel duration	0.001***	(0.000)	−0.011***	(0.000)		
Intercept	0.831***	(0.035)	0.926***	(0.126)	2.423***	(2.269,2.576)
Curvilinearity variable					EDF	P-value
Pavement ratio					4.461***	0.000
Street obstacles					7.630***	0.000
Street safety					6.185***	0.000
Street vitality					5.842***	0.000
Observations	21,897				14,603	
Log-Likelihood	−15215.110					
AIC	30546.220				131075.700	

*p < 0.10, **p < 0.05, ***p < 0.01. *NA* means that the relationship between this variable and AT duration was significant but not linear.

between pavement ratio (EDF = 4.461, $P < 0.001$), street obstacles (EDF = 7.630, $P < 0.001$), street safety (EDF = 6.185, $P < 0.001$), street vitality (EDF = 5.842, $P < 0.001$), and AT duration. A pavement ratio index smaller than 0.41 was negatively associated with AT duration. Nevertheless, the pavement ratio index had a slightly positive impact on AT duration when its value was larger than 0.41 (Fig. 5a). Fig. 5b indicated that the street obstacle index had a limited effect on AT duration when it was smaller than 0.021. When the street obstacle index exceeded 0.021, it was negatively related to older adults' AT duration. When the street safety index was smaller than 0.03, it had a positive relationship with AT duration. However, this association vanished when the street safety index exceeded 0.03 (Fig. 5c). Finally, a positive relationship between the street vitality index and AT duration was observed if street vitality fell into the range of 0.006–0.016 or was larger than 0.025 (Fig. 5d). We found no statistical evidence to support a significant relationship between street design and AT duration.

We also found significant negative associations between density of facilities (i.e., community centres, hospitals, clinics, and pharmacies), building density, population density, and AT duration. In contrast, older adults might have longer AT duration if their residences were surrounded with a greater number of educational and shopping facilities. For covariate variables, older adults in the

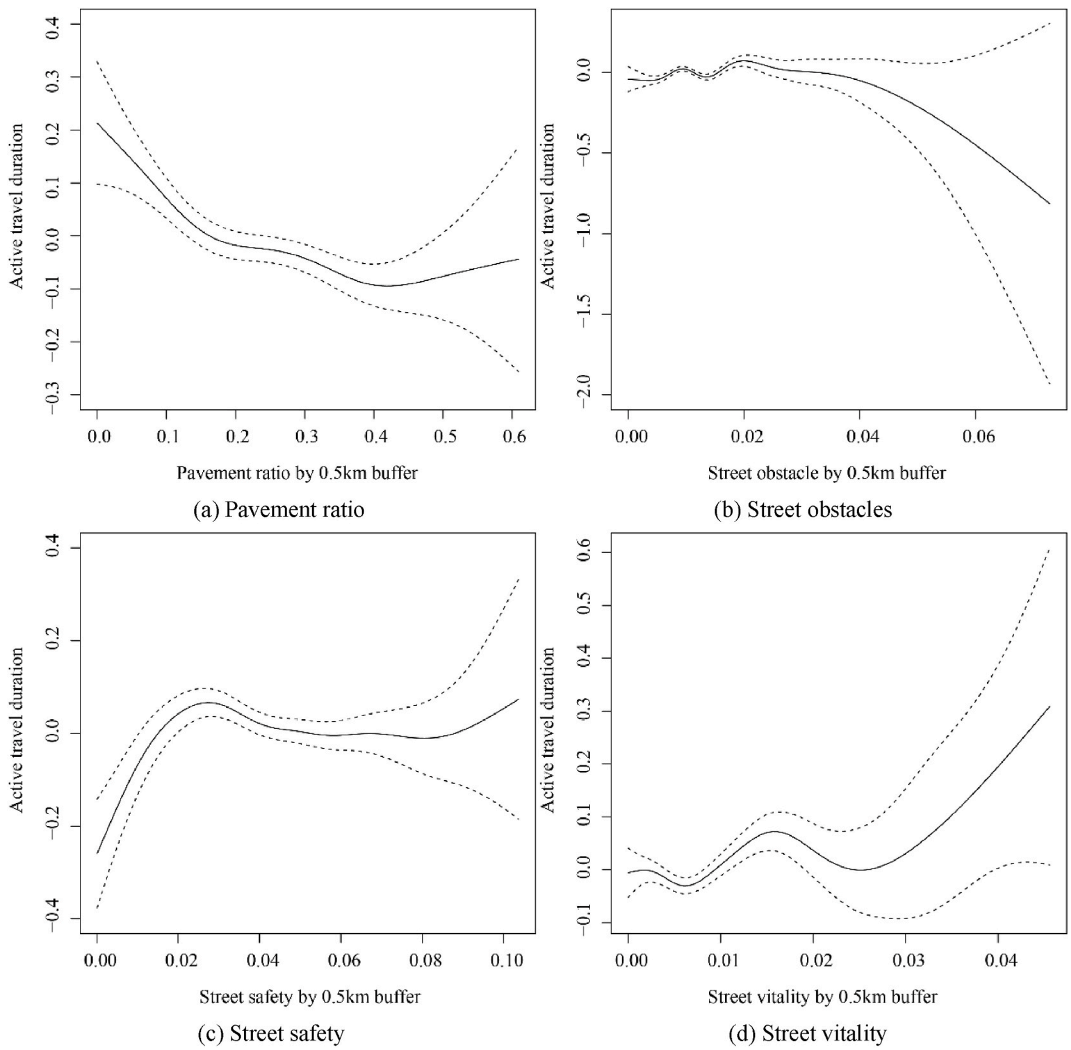


Fig. 5. Non-linear relationship between the pavement ratio, street obstacles, street safety, street vitality, and AT duration. Dashed lines represent the 95% confidence interval.

older age group, obtaining higher annual individual income, and conducting longer-distance travel were more likely to have a longer AT duration. However, older adults with better educational attainment (i.e., college or above) and more self-owned private cars tended to have a shorter AT duration.

3.3. Heterogeneous effects of respondents' age

Table 3 summarizes the results of the stratified analyses. The results of Model 3 suggest that the street greenery index and street design index had a stronger relationship with AT frequency among older adults aged 70–79 (i.e., the middle-old group). The street safety index and street vitality index only had a significant relationship with the likelihood of AT among older adults aged 70–79, while the street obstacle index had a stronger relationship with the number of AT trips among older adults aged 60–69 (i.e., the young-old group). Overall, age-friendly streetscape built environment attributes had stronger relationships with AT frequency for older adults aged 70–79.

Different from the results of Model 3, we found that age-friendly streetscape built environment attributes had stronger relationships with the AT duration for older adults aged 60–69. Although pavement ratio and street greenery had stronger relationships with AT duration for older adults aged 80–89 (i.e., the old-old group), street obstacles, street safety, and street vitality were only significantly associated with the AT duration for older adults aged 60–69. Among them, both street safety and street vitality had non-linear relationships with AT duration. Moreover, the curvilinear associations between street safety, street vitality and AT duration for older adults aged 60–69 were similar to those for street safety–AT duration and street vitality–AT duration for all older adult participants (Fig. 6).

Table 3
Results of age-stratified analysis.

	Model 3 (AT frequency)											
	60–69 years old (young-old group)				70–79 years old (middle-old group)				Older than 80 years (old-old group)			
	Logit model		Nb model		Logit model		Nb model		Logit model		Nb model	
	Coef. (S.E.)		Coef. (S.E.)		Coef. (S.E.)		Coef. (S.E.)		Coef. (S.E.)		Coef. (S.E.)	
Pavement ratio	0.119	(0.077)	0.103	(0.247)	−0.042	(0.142)	0.297	(0.509)	−0.020	(0.254)	−0.864	(0.990)
Street obstacles	0.579	(0.636)	4.965**	(2.026)	2.801*	(1.505)	−1.379	(4.338)	2.230	(1.864)	2.725	(9.104)
Street safety	−0.306	(0.480)	1.826	(1.516)	3.194***	(0.928)	−0.032	(3.253)	−0.508	(1.709)	−4.559	(6.521)
Street greenery	−0.167***	(0.055)	−0.155	(0.162)	−0.524***	(0.099)	−1.066***	(0.364)	0.259*	(0.154)	0.745	(0.783)
Street design	1.877**	(5.195)	1.082	(1.498)	2.097**	(9.329)	−5.398	(3.330)	−7.152	(15.080)	−4.180	(6.377)
Street vitality	1.327	(1.021)	−5.445	(3.446)	−5.110***	(1.758)	5.556	(7.224)	0.895	(3.171)	−8.067	(13.240)
Observations	16,920				3940				1037			
AIC	24259.390				5003.680				1106.727			
	Model 4 (AT duration)											
	60–69 years old (young-old group)				70–79 years old (middle-old group)				Older than 80 years old (old-old group)			
	Coef.		(91%CI)		Coef.		(91%CI)		Coef.		(91%CI)	
Pavement ratio	−0.419***		(-0.664,-0.175)		−0.606***		(-1.055,-0.157)		−1.171***		(-2.083,-0.258)	
Street obstacles	3.267***		(1.223,5.31)		0.255		(-3.609,4.119)		−2.784		(-11.286,5.718)	
Street safety	*NA*				0.383		(-2.458,3.224)		−1.683		(-7.432,4.066)	
Street greenery	0.221**		(0.043,0.399)		−0.014		(-0.324,0.296)		0.745**		(0.135,1.355)	
Street design	−3.942		(-2.527,1.643)		−2.688		(-5.786,9.410)		2.730		(-4.895,8.354)	
Street vitality	*NA*				0.917		(-5.397,7.232)		10.037		(-2.928,23.002)	
Curvilinearity variables	EDF		P-value		*NA*							
Street safety	5.578***		0.000									
Street vitality	6.022***		0.000									
Observations	11,039				2809				755			
AIC	99262.680				25104.700				6780.081			
Adjusted-R^2	0.049				0.074				0.029			

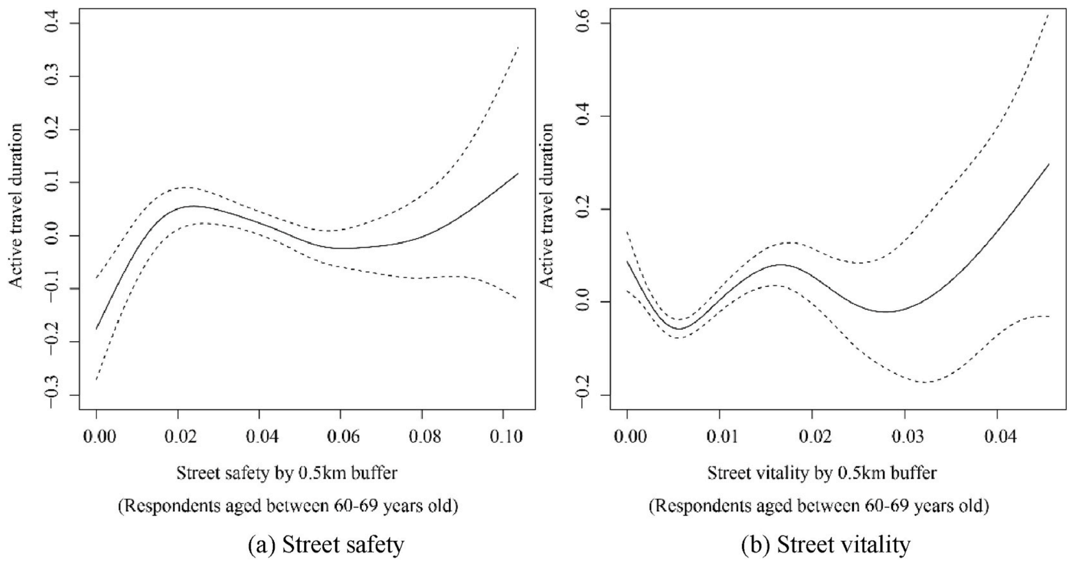


Fig. 6. Non-linear relationships of age-stratified analysis. Dashed lines represent the 95% confidence interval.

4. Discussion

4.1. Age-friendly (streetscape) built environments and older adults' AT

To our knowledge, this is the first attempt to examine the non-linear and threshold effects of age-friendly streetscape built environment on older adults' AT behaviours, with a particular focus on older adults' declining physical and mental situation. We developed a theoretical framework to identify specific (streetscape) built environment attributes which support or encourage older adults' independent AT. We observed that most streetscape built environment attributes influenced older adults AT behaviours in a non-linear way.

As one characteristic to satisfy older adults' *feasibility* need for AT, a pavement ratio smaller than 0.41 was negatively related to older adults' AT duration, while a pavement ratio larger than 0.41 was positively associated with AT duration. This finding has advanced existing studies in the United States (Hess et al., 1999) and the United Kingdom (Jessiman et al., 2023), which reported positive relationships between the presence of pavement and older adults' AT. Older adults tend to conduct AT of longer duration in areas with spacious pavements. Meanwhile, the negative effect of street obstacles on older adults' AT duration was observed when it exceeded the value of 0.021. It is reasonable that older adults become more vulnerable to environmental barriers (e.g., stairs, fences, and railings) on their walking or cycling journeys as they age (Barnett et al., 2017; Sun and Lau, 2021). Therefore, streets with excessive numbers of obstacles discourage older adults from undertaking longer AT journeys.

For attributes catering for older adults' *accessibility* need, the density of community centres, hospitals, clinics, and pharmacies had negative impacts on AT duration. This may be because older adults walk to facilities in local neighbourhoods for specific purposes, such as engagement in neighbourhood activities, health appointments, and buying medicines (Perchoux et al., 2019). In contrast, older adults might have longer AT duration if their residences are surrounded by more educational facilities (e.g., primary schools), shops, supermarkets, and malls. For one thing, it is common for Chinese older adults to provide childcare for their grandchildren and take them to or from school. Older adults are more flexible on these AT with their grandchildren and sometimes may casually travel to shops and parks (with their grandchildren) on their way back from school (Mackett, 2015). For another, shopping facilities, such as shops, supermarkets, and malls, encourage older adults to conduct longer AT. Shopping in markets is one common daily activity for Chinese older adults, who are more inclined to walk or to cycle to these shopping facilities (Cheng et al., 2019).

As for a characteristic meeting older adults' *safety* need, a *safety* index smaller than 0.03 was positively related to older adults' AT duration. However, this positive relation did not exist if the value of the safety index surpassed 0.03. The presence of safety-related street furniture, such as pavements, street lamps, or traffic lights, can encourage older adults to walk or cycle along streets for a longer time (Van Cauwenberg et al., 2011). Meanwhile, when such furniture is present, older adults then pay more attention to their quality during their AT journeys. For example, uneven pavements and broken lamps may be regarded as underlying hazards which discourage older adults from undertaking longer AT journeys.

In terms of the characteristics for older adults' *comfort* needs, we found a positive association between street greenery and older adults' AT duration. This finding was in line with existing studies (Yang et al., 2019, 2021). Greenery along streets may encourage older adults to walk or cycle for a longer time through creating a restorative environment and bringing forth feelings of contemplation (Kaplan, 1995). For *pleasurability* needs, the street design index (i.e., street furniture related to aesthetics and leisure) was positively associated with older adults' AT probability. Aesthetic and leisure furniture, such as fountains, chairs, and benches, not only brings convenience for older adults, but also makes streets more attractive for walking and cycling (Joseph and Zimring, 2007; Van

Cauwenberg et al., 2011). Meanwhile, street vitality had significant non-linear and threshold effects on older adults' AT duration. A positive relationship between the street vitality and AT duration can be observed if the street vitality falls into the range of 0.006–0.016 or is larger than 0.025. Lively streets, characterized by commercial and pedestrians' activities, present a stimulating scene for older adults and thereby attract them to socialize with others during their AT journeys (Cattell et al., 2008).

4.2. Other built environment and individual characteristics

We also found that building density and population density were negatively associated with older adults' AT duration. High building density and population density indicate a common lifestyle in high-density cities, in which older adults walk or cycle a short distance to facilities for daily maintenance activities (Cheng et al., 2019; Liu et al., 2023; Zang et al., 2019). These AT trips tend to be short journeys. Therefore, high building density, population density, and facilities related to daily maintenance activities encourage more AT trips among older adults but within shorter distances. As regards individual characteristics, older adults in the older age group, obtaining a higher annual individual income, were likely to conduct longer AT trips. In contrast, older adults with better educational attainment (i.e., college or above), and those who owned cars, tended to conduct AT trips of shorter duration.

4.3. Differences between young-old, middle-old, and old-old groups

Overall, age-friendly streetscape built environment attributes exerted stronger impacts on AT frequency for participants aged 70–79, and larger impacts on AT duration for participants aged 60–69. Notably, street greenery was positively associated with both AT frequency and duration among participants aged 80 and above. One possible reason is that with better functional abilities, the young-old and middle-old groups are more susceptible to characteristics of the streetscape built environment when conducting or making decisions about AT. Furthermore, the old-old group prefer to walk along streets with abundant greenery for leisure (Lau et al., 2021).

4.4. Limitations

Our study has three limitations. First, analysis of regression models may overemphasize certain streetscape built environment attributes derived from street view images. For example, street vitality index, which is computed based on but not limited to human activities, may vary depend on the time of day and season when the street view pictures were taken. Second, the algorithm used to identify objects in street view images has not been trained to understand whether an object is a barrier or amenity. Thus, some fences or stairs along the pavements serving for users may be identified as street obstacles. Third, we did not include the seasonality or weather in our model analysis, which have influence on older adults'AT. Due to the questionnaire design, we did not record the date of survey for each older adult participant.

5. Conclusion

We examined the non-linear relationships between streetscape built environments and older adults' AT patterns (i.e., frequency and duration). We observed that pavement ratio and street obstacles had negative impacts on older adults' AT duration within a certain range, and that when outside this range, the negative associations no longer held. Street safety, greenery, and vitality were positively associated with older adults' AT duration within a certain range. Street design exerted positive effects on the likelihood of AT. Age-friendly streetscape attributes showed a stronger relationship with the likelihood of AT among older adults aged 70–79, and larger impacts on AT duration for older adults aged 60–69. Notably, street greenery had positive impacts on both AT frequency and duration among older adults aged 80 and above.

This research also provides significant theoretical implications for studies on the relationship between built environment and older adults' AT behaviours, especially for creating age-friendly streetscape built environments in the context of Asian countries. Streetscape built environments exert positive impacts on encouraging older adults' AT. These positive impacts exist in young-old, middle-old, and old-old groups. Our findings offer practical insights for building age-friendly streetscape built environments which encourage more AT among older adults. First, we should ensure good-quality pavements for walking and cycling, and reduce obstacles on and along these pavements. Second, facilities for daily maintenance activities (e.g., health facilities, community centres, markets) can be located within and near to neighbourhoods to ensure convenient access for older adults, which will contribute to older adults' AT frequency. Meanwhile, it is advisable to place amenities for physical activities and entertainment in areas that are an appropriate distance away from neighbourhoods, which will increase the duration of older adults' AT to their destinations. Third, routine inspection and regular maintenance of safety-related street furniture should be carried out. Fourth, improvement of street greenery can attract different age groups of older adults to conduct AT along streets.

Consent for publication

Consent forms are available upon reasonable request.

Funding

This study was supported by Young Elite Scientists Sponsorship Program by CAST (No.2022QNRC001), National Natural Science

Foundation of China (No. 42301215), Independent research project of the State Key Laboratory of Subtropical Building and Urban Science (No.2023ZB17), Natural Science Foundation of Guangdong Province, China (No.2024A1515012607) and Hunan Provincial Natural Science Foundation of China (No.2024JJ6186).

CRediT authorship contribution statement

Yuqi Liu: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Xiaoge Wang:** Writing – original draft, Software, Methodology, Formal analysis. **Yuting Liu:** Writing – review & editing, Conceptualization. **Yiru Li:** Formal analysis. **Xiaoyi Ma:** Data curation. **An Jin:** Data curation. **Cheng Song:** Data curation. **Yao Yao:** Data curation.

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.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors would like to express sincre thanks to the editors and the two anonymous reviewers for their time and valuable comments in helping us to improve the quality of our paper. Besides, the authors would like to thank Mr. Jinheng Cen and Mr. Jing Liang for their contribution in data extraction of built environment attributes.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jth.2024.101834.

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