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Adolescents' environmental perceptions mediate associations between streetscape environments and active school travel

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ABSTRACT

Promoting adolescents' active school travel may support their health and wellbeing. Based on survey data of 473 adolescents in Guangzhou, China, and street view images, we employed generalized structural equation models to examine 1) the relationships between objective and perceived streetscape characteristics and adolescents' active school travel and 2) the mediating roles of perceived safety, walkability, and air pollution. Results showed that street safety, vitality, greenery, and vehicle volume were positively related to odds of active school travel, while higher pavement ratio was associated with lower odds of active school travel. Street safety, pavement ratio, and vehicle volume were related to active school travel through perceived walkability, while street vitality and vehicle volume were associated with active school travel through the perceived safety-walkability path and perceived air pollution-walkability path. Our findings provide practical insights that could help city planners to make urban street environments more child-friendly for adolescents' active travelling.

1. Introduction

Daily physical activity has numerous health benefits for adolescents, including a lower risk of overweight and obesity (Guthold et al., 2020). However, time spent in sedentary behaviour and physical inactivity has increased among Chinese adolescents (Xu et al., 2010). Only less than one-quarter of Chinese adolescents met the recommended level of physical activity (i.e., ≥60 min/day) in 2014 (Dong et al., 2020). Active school travel (AST), such as walking and cycling, is a means to increase adolescents' energy expenditure (Sun et al., 2018, Huang et al., 2017a, 2017b), contribute to their well-being (Waygood et al., 2017), and reduces traffic-related emissions (Woodcock et al., 2009, Rong et al., 2022).

Although the evidence on the associations between the urban built environment and adolescents' AST has been mounting (Ikeda

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et al., 2018a), the results of the direct relationships between the built environment and AST have been mixed across studies (Rothman et al., 2018, Ikeda et al., 2018b). One possible reason for these inconsistent results is that adolescents' environmental perceptions were typically ignored in the analysis. Some studies have suggested that parental perceptions of the built environment are likely to promote or inhibit adolescents' AST (Rothman et al., 2015, Salahuddin et al., 2016, Vanwolleghem et al., 2016). Still, with few exceptions (Ikeda et al., 2019), little attention has been paid to adolescents' environmental perceptions. Adolescents' perceptions of the surrounding environments are likely to matter in their travel mode choice to school because adolescents in high-school age may have pronounced self-efficacy and travel more independently without adult supervision (Ikeda et al., 2019, Buliung et al., 2017, Sweeney and Von Hagen, 2016).

Studies typically measure a neighbourhood's walkability based on indicators derived from a bird's eye perspective (e.g., street intersection density, accessibility of transit station, land use mix) (Bentley et al., 2018, Özbil Torun et al., 2020, Liu et al., 2019a, Liu et al., 2019b, Helbich et al., 2016). However, such operationalizations have failed to capture how people perceive streetscapes on the ground (Ikeda et al., 2019, Kaplan et al., 2016, Lam et al., 2022). To address this limitation, a few studies have applied machine learning and street view data to automatically assess the qualities of streetscapes, which could more accurately reflect adolescents' visual scenery on their daily trip to school (Yang et al., 2020, Łaszkiewicz and Sikorska, 2020). However, these streetscape-based studies have focused only on how greenery is related to AST; other streetscape attributes (e.g., pavement presence, safety, street vitality, motor traffic volume) remained unexplored.

Previous studies tend to focused on North America (Salahuddin et al., 2016, Rothman et al., 2015), European countries (e.g., UK), and some developed countries or regions in Asia (Leung and Loo, 2020, Susilo and Waygood, 2012, Kyttä et al., 2018), but Chinese high-density cities are underrepresented. Adolescents' travel behaviours in China may be quite distinct, not only due to a different social and cultural context (e.g., multi-generational household structure and lower car reliance) (Feng, 2017) but also because of differences in urban neighbourhood morphologies (e.g., compact urban form and rapid expansion of built-up areas).

To respond to these knowledge gaps, we examined the relationships between streetscapes and adolescents' AST in Guangzhou (China). We focused on the potential mediation effects of adolescents' streetscape environmental perceptions. We also partially addressed issues related to residential self-selection by removing home movers from the sample and explored effect heterogeneities across socio-demographics. Our study contributes to the literature twofold: first, it sheds light on the associations between adolescents' streetscape perceptions and AST and, second, it measures the qualities of streetscape environments at participants' homes and schools using street view imagery and machine learning.

2. Literature review

Numerous studies have investigated the complex determinants which promote or inhibit adolescents' AST (Ikeda et al., 2018a, Rothman et al., 2018, Vanwolleghem et al., 2016). Grounding on the socio-ecological model, AST encompasses multifaceted and multilevel determinants, such as the objective and perceived environmental factors, socio-demographics, intra-personal attributes, and travel-related characteristics (Mitra, 2013, Ikeda et al., 2019, Aliyas et al., 2022). Subsequently, each of these factors will be reviewed.

2.1. Built environment and adolescents' active school travel

Studies reported relationships between AST and aspects of the built environment, such as population and intersection density (Lu et al., 2019a, Moran et al., 2015, Oliver et al., 2015), land-use mix (Tewahade et al., 2019), transit and destination accessibility (Kaplan et al., 2016, Leung and Le, 2019), and urban design (Dias et al., 2019). A few stressed that the built environment should be measured at a micro-level (Saelens and Handy, 2008). Streetscapes not only matter for urban liveability but are also an outdoor space supporting residents to carry out activities, socialize, and travel (Ma et al., 2021b, Carmona et al., 2018).

Questionnaires have typically been used to audit streetscapes. Such studies have found that children's active commuting is positively associated with the street aesthetic (Kim and Heinrich, 2016), pavement availability (Auguste et al., 2020), and the multi-functionality of the street (Sun et al., 2018), while heavy traffic volume, a lack of safety facilities, and increased risk of traffic incidents are inversely associated (Christiansen et al., 2014, Timperio et al., 2006). However, manually auditing streetscapes is time-consuming, costly, and labour-intensive and may not represent the actual streetscape accurately. To overcome this limitation, machine learning and street view images have been proposed to assess streetscapes (Yang et al., 2019, Yang et al., 2021).

2.2. Mediating effects of environmental perception on the built environment-AST relationship

Both social cognitive theory (Rahman and Sciara, 2022) and social ecological theory (Acheampong and Siiba, 2018) emphasize the differences between objectively measured built environment and perceived built environment and highlight that people's environmental perceptions is influenced by person-level and social factors (Ma and Cao, 2017). This implies that different people may have different perceptions of the same built environmental aspect which, in turn, could lead to different travel patterns (Ewing and Handy, 2009). Consequently, the perceived environment may mediate the relationship between the objectively measured built environment and people's travel behaviour.

The perception of walkability, which refers to the extent of how user-friendly a walking environment is perceived by pedestrians, has received increased attention (Yu and Zhu, 2016, Christiansen et al., 2014, Pocock et al., 2019). Different assessment tools have been used in Western countries (Liao et al., 2022). For example, a US study found that people might perceive a street more walkable and cyclable if the street was well-shaded by trees and had clean and wide-enough pavements separated from traffic lanes (Yu and Zhu, 2016). Other studies examined the relationship between environmental attributes and perceived walkability by means of the NEWS scale (Kerr et al., 2016, Sallis et al., 2020). Even though not always consistent, these studies found that perceived walkability was positively associated with land use mix, residential density, street aesthetic, traffic safety, etc. (Rosenberg et al., 2009, Ducheyne et al., 2012, Dias et al., 2019, Martin et al., 2021). Nevertheless, much less is known about how streetscape characteristics measured through street view data relate to adolescent's perceived walkability and their AST, especially in the Chinese context.

In addition to walkability, perceived safety remains an important factor of concern for adolescents' AST (Zhou et al., 2010). For example, studies conducted in Belgium, Australia, and Canada found that perceived street safety was positively associated with children's active travel (Vanwolleghem et al., 2016, Pont et al., 2013, Buttazzoni et al., 2019, Fusco et al., 2012). However, only a few studies have focused on the mediating effects of perceived safety on the built environment-AT relationships, and the results have been inconsistent. Some found that both street vitality and safety facilities, such as the presence of shopkeepers, diverse human activities, and windows, added to the perceived street safety, as many people are watching the streets, which is positively associated with people's active behaviours (Istrate and Chen, 2022). However, some studies reported null associations between street safety and travel behaviours (Timperio et al., 2004, Carver et al., 2005). Some developed countries have introduced active policy interventions to improve adolescents' AST (Boarnet et al., 2005). For example, the Safe Route to School programme in Denmark and the US improved the walking and cycling environments for children and adolescents by controlling traffic and enhancing active travel facilities (Mcmillan, 2005, Carver et al., 2008). Therefore, paying attention to adolescents' perceived street safety can provide a reference for child-friendly cities.

Previous studies also showed that exposure to air pollution may discourage people's willingness to make active travel, partly due to the negative health impacts from air pollutants (Singh et al., 2021, An et al., 2019). However, perceived air pollution as a mediator between the objective built environment and people's travel patterns remained unaddressed, although some studies have found that, with an increase in motor traffic volume, active travellers are exposed to various traffic-related pollutions, which has an inhibitory effect on the likelihood of them selecting active travel (Leung and Le, 2019). Despite increasing empirical evidence on the direct AST-built environment associations, there is a lack of evidence on the relationships between perceived environmental qualities and AST and the possible mediation effects of perceived environments in the Chinese context. Neglecting the possible mediation effects of perceived environments may lead to biased results (Gan et al., 2021).

2.3. Other factors influencing adolescents' AST

Socio-demographic characteristics affecting adolescents' AST have mainly focused on the attributes of students and their caregivers, such as gender, age, economic status, educational attainment, and car ownership (Medeiros et al., 2021, Rothman et al., 2018, Lam and Loo, 2014). Some studies concluded that adolescents with lower economic status and less car accessibility have a higher likelihood of AST. Specifically, a US study found that students with lower income use active travel modes to school more often than higher-income students (Mcdonald, 2008). A study from Beijing (China) suggested that children from households with a private car were more likely to travel by car (Li and Zhao, 2015). However, results were inconclusive on other factors. For example, although some studies indicated that boys have a higher AST likelihood than girls, girls travelled less independent because of their vulnerability, some reported no differences (Medeiros et al., 2021). Parental education also be a possible moderator, which needs further verification in more empirical research (Rothman et al., 2018).

Travel-related characteristics also have an essential impact on AST. Travel distance and time, measured objectively and self-reported, are likely negatively associated with AST (Pont et al., 2013). A student's travel mode was also related to whether the student travels independently or was accompanied by caregivers or friends. For example, a study in Shenzhen (China) found that children who travelled with parents/grandparents had a lower AST likelihood than those who travelled alone (Sun et al., 2018), while an Australian study found that boys who travelled with friends had a higher likelihood of AST (Leslie et al., 2010).

However, most existing studies do not consider residential self-selection on AST (Ettema and Nieuwenhuis, 2017, Handy et al., 2007). Residents may live in neighbourhoods reflecting their socio-demographics and preferences, thus influencing travel patterns (Cao et al., 2007). However, the effect and the magnitude of residential self-selection has been controversial in the literature (Zang et al., 2019, Huang et al., 2017a, 2017b, Wang and Lin, 2019), because people may not be able to choose their residence entirely based on their preferences, especially in developing countries. For example, in China, residents living in Danwei community or social welfare housing typically have no or little residential choice (Wang and Zhou, 2017). In case of AST studies, the possibility of residential self-selection should not be neglected. Many parents may attach more importance to educational resources, and they may change their place of residence to have access to better schooling (Rong et al., 2022). Studies conducted in Texas (US) suggested that the self-selection of a walkable neighbourhood and a "close to school" home were associated with AST, and a positive parental attitude to walking environments was positively associated with children's walking to school (Yu and Zhu, 2013, Yu and Zhu, 2016). Whether or not residential self-selection is also significantly related to Chinese adolescents' AST needs to further investigation due to the special "school district policy" among public schools.

3. Materials and methods

3.1. Survey data

Travel data were collected through a survey carried out in Guangzhou, China, from April to September 2018. We randomly sampled 11 neighbourhoods from seven inner-city districts of Guangzhou (i.e., Tianhe, Yuexiu, Haizhu, Liwan, Baiyun, Huangpu, and Panyu) by means of a multistage stratified probability proportional to size sampling technique. In each neighbourhood, we invited 30 to 70 middle school students aged 12–18 through convenience sampling to complete a face-to-face questionnaire. The questionnaire included items capturing respondents' socio-demographics, travel behaviours, subjective well-being, and health-related information. In total, we recruited 502 respondents.

Respondents stated their home and school addresses. The addresses were manually geocoded by the research team. We then placed a 500 m circular buffer on each respondent's home and school location to capture streetscape and built environmental characteristics. Our buffer approach to delineate the geographic context circumvents methodological issues of administrative neighbourhood units (Flowerdew et al., 2008). However, because our results might be sensitive to the selected buffer width, we also delineated the geographic context using 800 m and 1,000 m buffers.

3.2. Dependent variable

The trip mode, coordinates of trip origin and destination, trip purpose, and the start time and end time per trip were based on a 24-h travel diary. We considered trips from home to school and vice versa on working days. Respondents could choose their travel mode based on eight possibilities: walking, cycling, car, bus, metro, etc. If there were multimodal trips, respondents chose the travel mode with longest duration. Our dependent variable was mode choice per trip reclassified into active (i.e., walking and cycling) and motorized. In total, after excluding respondents with no school trips on weekdays and some missing questionnaire information (N = 29), our final sample included 473 respondents, who provided 1,002 school trips.

3.3. Independent variables

We employed street view data taken in 2016 from Tencent Map (https://map.qq.com/) to measure respondents' street environment. Sampling locations were created every 50 m along the street network based on the OpenStreetMap data (https://www.openstreetmap.org). Four street view images in the four cardinal directions of each sample point were collected by querying the application programming interface of Tencent Maps. We obtained 283,436 street view images at 70,859 sample locations.

As done elsewhere (Helbich et al., 2019, Yao et al., 2021, Wang et al., 2019), we trained a convolutional neural network (i.e., the FCN-8s) based on the ADE20K scene parsing and segmentation database to identify 151 different street objects within each image (Yao et al., 2019, Zhou et al., 2018, Zhou et al., 2017). The segmentation accuracy of the overall FCN-8s model reached 81.44% in the training set and 66.83% in the test set (Yao et al., 2019) (https://sceneparsing.csail.mit.edu). Finally, we determined the pixel-wise proportion of each object per image, and averaged the values across the four cardinal directions.

We assessed the following five streetscape attributes based on the segmented images within each buffer. Measuring street safety facilities and vitality represented how pedestrians perceive street environments (Kruse et al., 2021, Kang et al., 2020), while pavement ratio, street greenery, and the vehicle volume captured physical features along the street (Yang et al., 2020, Wu et al., 2020, Sun et al., 2018, Eldeeb et al., 2021, Christiansen et al., 2014). First, safety facilities were defined as the average value of the sum of pixels classified as street furniture (i.e., fences, streetlights, traffic lights, cameras, and windows). Second, street vitality was calculated as the average value of the sum of pixels classified as pedestrians, bicycles, booth, trade name, and signboard features of the sample locations. Third, pavement ratio was defined as the pixels ratio of the pavement to the sum of the pavement and roadway. Fourth, street greenery was represented through the average greenery across the sampling locations. Finally, vehicle volume referred to the average value of

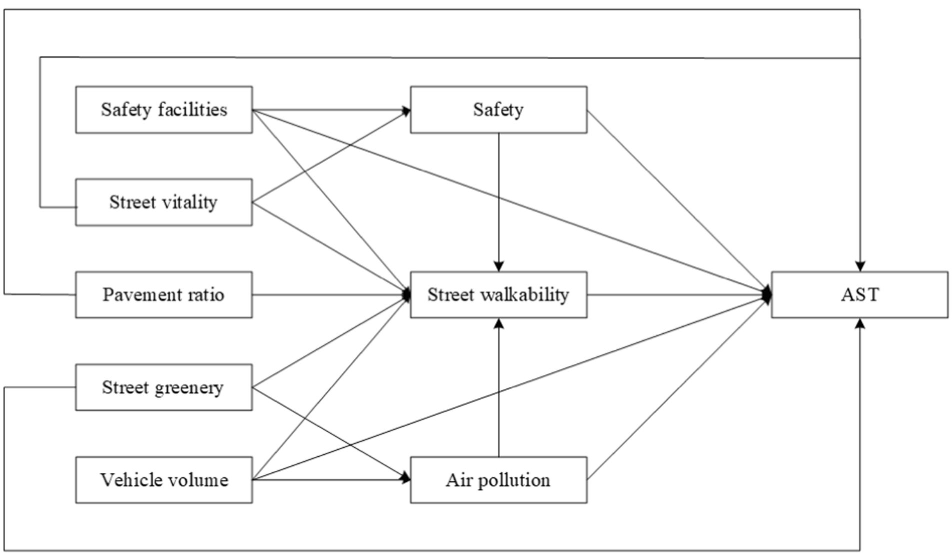

Fig. 1. Conceptual framework of the links between streetscape attributes, environmental perceptions, and AST.

the sum of pixels classified as motor vehicles. See Supplementary Table S1 for further details.

3.4. Mediators

As illustrated in our conceptual model (Fig. 1), we explored how the relationship between streetscapes and adolescents' AST was mediated through adolescents' perceived safety, walkability, and air pollution. Considering that both street vitality and safety facilities may make people feel secure (Istrate and Chen, 2022), we hypothesized that these aspects are indirectly related to AST through adolescents' perceived safety. Given that pedestrians and cyclists near motor vehicles are exposed to increasing levels of unpleasant noise and air pollution when there is a lack of street greenery, which makes adolescents feel uncomfortable (Gelb and Apparicio, 2021, Łaszkiewicz and Sikorska, 2020), we included perceived air pollution as a mediator. Because not only physical streetscape attributes are recognized to shape walkability but also perceived street qualities may affect how walkable a street is (Ewing and Handy, 2009), we hypothesized that streetscape attributes, perceived safety, and air pollution may affect AST indirectly through perceived street walkability.

Perceived safety, street walkability, and air pollution were assessed based on a 5-point Likert scale by asking respondents to what extent they agree the following statements about the street environment around home and school: "I feel very safe even when I travel on the street alone", "The street walkability is very good", and "The air quality of the street is very poor". Subjects' responses ranged from totally disagree (=1) to totally agree (=5). A higher score for safety and street walkability indicated better perceived environmental qualities. A higher air pollution score indicated that subjects perceived more severe air pollution, which negatively affect pedestrians' travel experience (Ma et al., 2021a).

3.5. Covariates

We measured the following built environmental attributes in each buffer: intersection density, public transit (i.e., bus stop and metro) density, density of recreational facilities (i.e., playgrounds, cinemas, music halls and so on), density of security facilities (i.e., police stations and so on), as well as density of parks and public squares by using point of interest (POI) data. Supplementary Table S1 provides in-depth descriptions of each variable.

As person-level covariates, we included gender (male vs. female), education level (junior high school vs. senior high school), family relationship (inharmonious vs. harmonious), hukou status (i.e., a system of household registration in China, which identifies a person as a permanent resident of an area and includes identifying information such as name, birth, marriage, move and so on) (local hukou vs. non-local hukou), number of family members, economic status of the household (poor vs. fair vs. good), number of cars per household, highest educational level of parent(s) (junior high school or below vs. senior high school vs. college or above), and employment status of parent(s) (full-time job vs. others). For measuring the household economic status, we invited the respondents to answer a question with 5-point Likert scale: "How is your household economic status?" Subjects' responses ranged from very low (=1) to very high (=5). Similarly, we also asked the respondents to answer the question about family relationship with 5-point Likert scale: "How is your relationship with your family members?" Subjects' responses ranged from very harmonious (=1) to very inharmonious (=5). We also included respondents' residential moving history ("movers" vs. "non-movers") to address residential self-selection (Handy et al., 2007, Wu et al., 2021). "Movers" are those who have at least one residential relocation since birth.

As trip-specific covariates, we calculated the road network distance from the respondents' home address to their school address, and included travel companionship (travel alone vs. travel with families vs. travel with friends).

3.6. Statistical analyses

We fitted generalized structural equation models (GSEMs) with a logit link function to assess associations between objectively measured streetscape attributes, environmental perceptions, and AST. We were unable to use multilevel GSEMs due to the small number of 11 sampled neighbourhoods in our survey. Once the number of neighbourhoods is too small, the estimates of 'group effects' will be unreliable (standard errors will be too small), and the variance components will be under-estimated. This may lead to incorrectly estimated intraclass correlation coefficients (ICCs) (Maas and Hox, 2005, Bryan and Jenkins, 2016). Thus, we used single-level GSEMs with robust standard errors. Maximum likelihood was used to obtain the parameter estimates. We used *nlcom* command in STATA 14.0 to calculate the indirect effects and standard errors. The goodness-of-fits for different models were compared with the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). Multicollinearity was tested with variance inflation factors (VIF).

We used several serial mediation models to test the pathways linking streetscape attributes to adolescents' AST. Model 1 was a serial mediation model (Fig. 1). This base model only included the relationship between AST and the streetscape attributes around home and three mediators (i.e., perceived safety, street walkability, and air pollution). Model 2 also included the environmental setting around school sites which may affect adolescents' AST. We determined the total effect of each streetscape attribute by averaging residential and school-based streetscape attributes within school buffers weighted by 0.5 (Model 2). Model 2 was based on the average score of respondents' perceived safety, street walkability, and air pollution around their home and school as mediators. Model 3 and 4 addressed residential self-selection through stratifying the data into movers and non-movers (Wu et al., 2021). Finally, we stratified the analyses by gender, household economic status, car ownership, and the highest educational level of parent(s) (Model 5–8).

4. Results

4.1. Descriptive statistics

Table 1 summarizes the descriptive statistics of the variables ($N = 1,002$). Active travel accounted for 39.42% of the total trips, which is lower than in Beijing (51%) and Shanghai (56%) (Li et al., 2015, Zhu et al., 2021). On average, the value of safety facilities, street vitality, and vehicle volume within home and school buffers were comparable. The pavement ratios of home and school buffers were 0.28 and 0.26, and the streetscape greenery of home and school buffers were 0.28 and 0.25 respectively. For the three environmental perceptions (i.e., perceived safety, street walkability, and air pollution), the average perceived values of safety, street walkability, and air pollution at home were 3.91, 4.02, and 2.52 respectively, while the average values around school were 3.94, 4.04, and 2.54 respectively.

4.2. Relationships between streetscape attributes, three mediators, and AST

There was no evidence of variable multicollinearity. Both the AIC and BIC scores suggested a better model fit when the built environmental variables around home and school were included (Model 1 vs. Model 2) (AIC: 6,530.206 vs. 6,191.728; BIC: 6,913.166 vs. 6,574.689). Therefore, we discuss only Model 2 shown in Fig. 2. The total effects for all variables are given in Supplementary Table S2. The direct effects of the streetscape attributes only around home on AST (Model 1) are depicted in Supplementary Figure S1.

The five streetscape attributes had direct associations with AST. Except for the negative relationship of pavement ratio, an increase in the other four streetscape attributes was significantly related with a higher AST likelihood. Street walkability was positively associated with AST, while safety and air pollution were not directly related with AST. Street vitality was positively associated with perceived safety, higher vehicle volume was related to more severe air pollution, and safety facilities, pavement ratio, and vehicle volume had positive relationships with street walkability. We also found that a higher safety perception was associated with more street walkability, while air pollution showed an inverse relationship with street walkability.

Table 1
Summary statistics of the sample ($N = 1,002$).

Characteristics	Proportion / Mean (SD)	Characteristics	Proportion / Mean (SD)
Dependent variables (%)		Family relationship (%)	
Active travel	39.42	Inharmonious	11.08
Walking	31.34	Harmonious	88.92
Cycling	8.08	Hukou status (%)	
Other modes of travel	60.58	Local hukou	72.75
Private car	6.59	Non-local hukou	27.25
Bus	50	Number of family members	3.73(0.99)
Subway	3.99	Household economic status (%)	
Independent variables		Poor	3.49
Streetscape built environment_home		Fair	34.53
Safety facilities	0.01(0.00)	Good	61.98
Street vitality	0.01(0.00)	Car number	0.45(0.55)
Pavement ratio	0.28(0.07)	Highest education level of parents (%)	
Streetscape greenery	0.28(0.06)	Junior high school or below	1.60
Vehicle volume	0.05(0.01)	Senior high school	64.67
Streetscape built environment_school		College or above	33.73
Safety facilities	0.01(0.00)	Employment status of parents (%)	
Street vitality	0.01(0.00)	Full-time job	89.42
Pavement ratio	0.26(0.07)	Others	10.58
Streetscape greenery	0.25(0.06)	Trip characteristics	
Vehicle volume	0.05(0.02)	Distance from home to school (m)	3776.41 (3384.33)
Mediators		Companionship information (%)	
Environmental perception around home		Travel alone	58.08
Safety	3.91(0.64)	Travel with families	8.98
Street walkability	4.02(0.59)	Travel with friends	32.94
Air pollution	2.52(0.63)	Other built environmental attributes	
Environmental perception around school		Built environmental attributes_home	
Safety	3.94(0.65)	Intersection density	85.29(64.59)
Street walkability	4.04(0.59)	Public transit density	7.94(4.49)
Air pollution	2.54(0.69)	Recreational facilities density	28.58(15.61)
Covariates		Security facilities density	5.74(5.25)
Socio-demographic characteristics		Parks and square density	0.71(0.99)
Gender (%)		Built environmental attributes_school	
Male	49.60	Intersection density	99.28(74.86)
Female	50.40	Public transit density	6.65(3.06)
Grade (%)		Recreational facilities density	25.15(19.75)
Junior high school	62.08	Security facilities density	4.67(4.72)
Senior high school	37.92	Parks and square density	0.76(1.72)

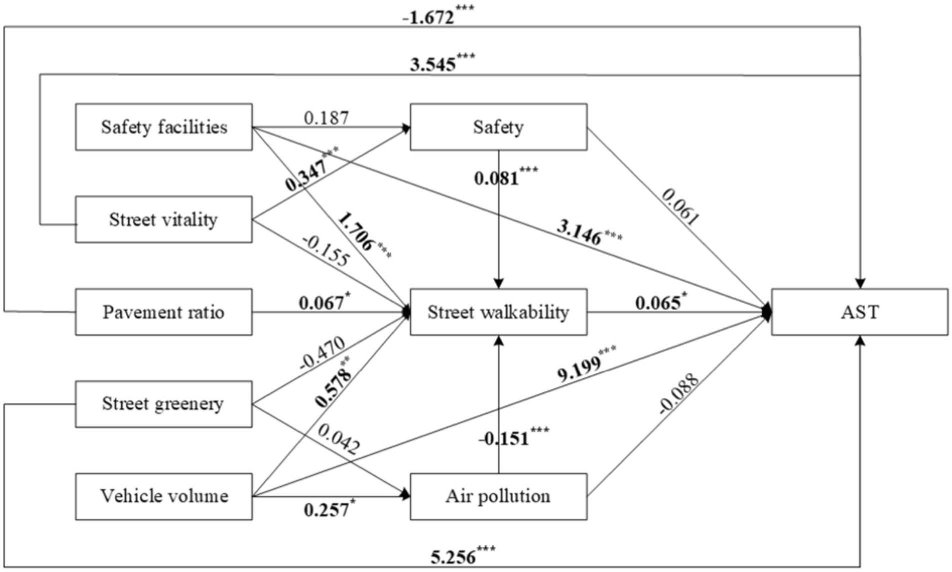

Fig. 2. Path diagram when environmental exposure around home and school were included (Model 2). (Significance levels: * p < 0.10, ** p < 0.05, *** p < 0.01. The model was adjusted for all covariates shown in Table 1.).

Table 2 shows the direct, indirect, and total effects of streetscape attributes on AST. Results show that all five streetscape attributes were significantly and robustly associated with AST, regardless of whether the environment around school was considered or not. We found that safety facilities were indirectly and positively associated with AST through perceived walkability, and pavement ratio was indirectly and negatively related to AST through perceived walkability. When environmental exposures around school were considered, we found that street vitality was indirectly associated with the likelihood of AST through the serial perceived safety-perceived street walkability path. In terms of vehicle volume, its positive relationship with AST turned out to be mediated by perceived walkability and perceived air pollution-walkability path. There was no evidence that street greenery was associated with AST indirectly through perceived environmental qualities. Model 2 indicated that the relationship between safety facilities, street vitality, pavement

Table 2
The direct, indirect, and total effect of the streetscape attributes on AST.

Variable	Model1			Model2		
	Built environment in home buffers			Built environment in home and school buffers		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
	Estimate (S.E.)	Estimate (S.E.)	Estimate (S.E.)	Estimate (S.E.)	Estimate (S.E.)	Estimate (S.E.)
Streetscape attributes						
Safety facilities (SF)	1.753**(0.717)		1.849***(0.724)	3.146***(1.125)		3.235***(1.103)
SF → safety → AST		−0.006 (0.020)			−0.016 (0.038)	
SF → walkability → AST		0.102* (0.125)			0.104* (0.189)	
SF → safety → walkability → AST		0.001 (0.001)			0.001 (0.002)	
Street vitality (SV)	6.659***(1.572)		6.725***(1.569)	3.545***(0.980)		3.507***(0.978)
SV → safety → AST		0.023 (0.072)			−0.030 (0.060)	
SV → walkability → AST		0.046 (0.060)			−0.010 (0.021)	
SV → safety → walkability → AST		−0.002 (0.003)			0.002* (0.003)	
Pavement ratio (PR)	−1.024***(0.376)		−1.003***(0.376)	−1.672***(0.323)		−1.668***(0.323)
PR → walkability → AST		0.020* (0.025)			0.004* (0.009)	
Streetscape greenery (SG)	5.264***(1.721)		5.279***(1.724)	5.256***(1.765)		5.230***(1.763)
SG → air pollution → AST		0.000 (0.003)			0.003 (0.013)	
SG → walkability → AST		0.015 (0.045)			−0.029 (0.057)	
SG → air pollution → walkability → AST		0.000 (0.002)			−0.000 (0.002)	
Vehicle volume (VV)	10.553***(1.506)		10.611***(1.510)	9.199***(1.459)		9.248***(1.470)
VV → air pollution → AST		−0.004 (0.082)			0.017 (0.056)	
VV → walkability → AST		0.067* (0.086)			0.035* (0.065)	
VV → air pollution → walkability → AST		−0.005* (0.007)			−0.002* (0.005)	
AIC	6662.144			6344.176		
BIC	7040.195			6722.227		

Standard errors in parentheses; * p < 0.10, ** p < 0.05, *** p < 0.01.

ratio, vehicle volume, and AST were both partially mediated by perceived street environments, even though the indirect effects were relatively small. Results suggest that using 800 m and 1,000 m buffers will not make substantial change in our conclusion (Supplementary Table S3).

Considering the other built environment features (Supplementary Table S2), intersection density and density of security facilities within home buffers were both negatively related with AST (Model 1). When simultaneously considering the built environment at both home and school buffers, the public transit density was positively associated with the likelihood of AST, while the density of recreational facilities showed a negative relationship (Model 2).

Boys were more likely to travel actively to school than girls (Supplementary Table S2), while adolescents with harmonious family relationships, those having a local hukou, and those with access to a car were less likely to use AST. Compared with adolescents' whose parents' educational level was junior high school or below, adolescents with higher-educated parents had a lower AST likelihood. Finally, adolescents whose parents had full-time job showed lower likelihood of AST. Considering the trip-related characteristics, we found that there were lower AST likelihood with increasing home-school distance. Compared with adolescents who travelled alone, those who travelled with family members had a lower AST likelihood, and those who travelled with friends had a higher likelihood of AST (Supplementary Table S2).

4.3. Difference in streetscape attributes-AST relationship between movers and non-movers

Table 3 shows the results for movers and non-movers. We found differences in the relationships between the streetscape attributes and AST across both strata. In line with the full sample results, street safety facilities and greenery were positively related with AST for non-movers, and pavement ratio showed a negative relationship with non-movers' likelihood of AST. However, there was no further evidence that street safety facilities, pavement ratio, and greenery were associated with AST among movers.

4.4. Heterogeneous effects of respondents' socio-demographic characteristics

Stratified analysis results are shown in Supplementary Table S4. Streetscape attributes had a stronger relationship with AST for girls. For household economic status, street vitality, greenery, and vehicle volume showed a stronger association with the higher-income group, while safety facilities and pavement ratio had stronger relationship with the lower-income group. For car ownership, street safety facilities, vitality, and greenery had a stronger relationship with AST for respondents without a car, while the effect size of pavement ratio and vehicle volume were stronger for car-owners. Street vitality and greenery were related to a higher likelihood of AST only for the lower-educated group, while safety facilities, pavement ratio, and vehicle volume were more strongly related with AST among the higher-educated ones.

5. Discussion

This study assessed the relationships between streetscapes and adolescents' AST. We found that the likelihood of AST was directly associated with safety facilities, street vitality, pavement ratio, greenery, and vehicle volume around home and school. However, the relationships between AST and safety facilities, street vitality, pavement ratio, and vehicle volume were partially mediated by adolescents' environmental perception. Associations between streetscapes and AST were more pronounced among non-movers, and moderated by gender, household economic status, car ownership, and parents' educational attainment.

5.1. The direct effects of streetscape attributes on AST

Street safety facilities at home and school were positively related with AST, which is in line with others (Mcmillan, 2007, Hume et al., 2009, Timperio et al., 2006, Panter et al., 2013). For example, in a Californian study (US) the number of windows facing the

Table 3
The total effect of the streetscape attributes on AST for movers versus non-movers.

Variable	Model3		Model4	
	Movers		Non-movers	
	Estimate	(S.E.)	Estimate	(S.E.)
Streetscape attributes				
Safety facilities	1.068	(3.115)	4.427***	(1.367)
Street vitality	3.500*	(1.891)	5.106***	(1.230)
Pavement ratio	−1.311	(1.026)	−1.668***	(0.398)
Streetscape greenery	−1.072	(2.997)	9.547***	(2.407)
Vehicle volume	15.489***	(5.036)	8.017***	(1.901)
Constant	54.674***	(9.582)	66.054***	(6.364)
Number of respondents	320		682	
AIC	2112.737		4139.529	
BIC	2406.666		4483.431	

Standard errors in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The model was adjusted for all covariates shown in Table 1.

street was positively associated with AST, as “eyes on the street” may increase safety and enhance active travel comfort (Mcmillan, 2007). Two Australian studies (Hume et al., 2009, Timperio et al., 2006) and one conducted in England (Panter et al., 2013) found that higher streetlight density was positively associated with adolescents’ AST. In the study area of this paper, Guangzhou, adolescents from some middle schools and most high schools were asked to take night self-learning in their school, which make them go home until after the sunset. In this case, the street lights could be very important for the adolescents’ likelihood of AST.

Our results showed that street vitality had a positive relationship with AST. Previous studies defined street vitality through several aspects, such as the physical (e.g. pavement width, street furniture, and street vegetation), functional (e.g. accessibility to services, commercial distributions), and social (e.g. safety, human activities, sense of place) characteristics of streets, and emphasized its critical importance in promoting people’s active travelling and continuous pedestrians activities (Istrate and Chen, 2022). For example, a US study indicated that the complexity of streets formed by various business types was one of the main contributors to enhancing pedestrians’ trips (Park and Garcia, 2019), and findings from developing countries including Vietnam and Thailand suggested that streets with some informal vendors were more attractive for active travellers (Leung and Le, 2019, Oranratmanee and Sachakul, 2014). We also observed a positive and direct relationship between the street greenery around home and school and AST. Greenery during daily active school travel provides not only ecosystem services (Kabisch, 2015) but may also stimulate psychological restoration leading to more active school trips (Łaszkiewicz and Sikorska, 2020, Sun et al., 2018).

Somewhat unexpected was the negative relationship between the pavement ratio and AST. Some earlier studies had reported a positive relationship between the presence of pavements and people’s active travelling (Wang et al., 2022, Eldeeb et al., 2021). However, two Dutch studies found limited support that the presence of pavements is crucial in explaining active travel mode choice, which may be because of the omnipresence of cycle paths and sidewalks (Ton et al., 2019, Helbich, 2016). A study from Germany found that roads having a pavement width of less than 1 m was positively related with the likelihood of driving to school rather than walking (Scheiner et al., 2019). Our finding could be related to the way pavement ratio was assessed, namely, via street view imagery, which cannot distinguish bike lanes from pavements.

Finally, we found a positive relationship between vehicle volume and AST. This finding was also inconsistent with previous studies, which had reported that high traffic volume was a potential barrier to active travel (Lutfur Rahman et al., 2022, Lu et al., 2019b). Nevertheless, our finding echoes the result of a study conducted in Denver, which suggested that on vibrant streets, residents seemed to worry less about higher traffic volumes (McAndrews and Marshall, 2018). One possible explanation is that there are spurious traffic-AST relationships. Our neighbourhoods were in the inner-city districts of Guangzhou, where adolescents tend to have shorter commuting distance and are exposed to higher traffic volume (the relationship between traffic presence and distance from home to school was negative and statistically significant).

5.2. Effects of three perceived mediators

As found elsewhere (Witten et al., 2022, Bennetts et al., 2017), street vitality was significantly and positively correlated with perceived safety, as pedestrians and activities on the street, and the presence of a variety of types of commercial facilities, can reduce crime and increase people’s perceived safety. However, we found no evidence that perceived safety played a statistically significant mediating role in the relationship between the street furniture, vitality, and the likelihood of AST. Possible explanations include the following. First, parents’ perceived street safety may be more important in shaping adolescents’ travel behaviours (Ikeda et al., 2019, Vanwolleghem et al., 2016). Second, some adolescents with a lower economic status may be limited in their choice of travel modes, and so perceived street environments may have little impact on their travel modes (Martin et al., 2021). Third, pedestrians’ perception of street safety may differ from the real safety situation of the streets, and those who regularly travel actively may be more familiar with street safety (Carver et al., 2008). In addition, we found a positive relationship between vehicle volume and perceived air pollution, while the vehicle volume-likelihood of AST relationship was not mediated by the level of air pollution. It could be that in our data, most of the respondents did not think that there was severe air pollution around their home and school (94% and 93% respectively). Second, urban residents may be less sensitive to traffic-related air pollution because of their long-term exposure to such conditions (Liu et al., 2022).

Our study found that perceived walkability played a significantly mediating role in the relationship between the safety facilities, pavement ratio, vehicle volume, and AST. Street vitality was indirectly related with AST through safety-walkability path, while vehicle volume had an indirect significant relationship with AST through air pollution-walkability paths. Among these, street vitality was essential for shaping a walkable and healthy urban environment (Paköz and Işık, 2022). On the contrary, increased air pollution may have an inhibitory effect on perceived walkability (Su et al., 2016).

5.3. Residential self-selection

Results concerning residential self-selection showed marked differences in the streetscape attributes-likelihood of AST relationship between the movers and non-movers. A possible explanation is that in our data, movers whose relocation purpose was to improve their living conditions accounted for 64.02% of all movers, and they were able to move out of negative living environments. This may indicate that for most of the movers, the overall quality of their living environment was relatively good, so their travel behaviours may be more affected by other factors. Non-movers’ travel behaviours were more likely to be affected by streetscapes (Wu et al., 2021), as they lived in one place for long periods of time and were likely to adjust their preferences and travel behaviours to fit with the environmental attributes around their residence.

5.4. Limitations

This study had some limitations. First, the street view data collected in 2016 were not exactly temporally aligned with the survey data collected in 2018. The misalignment may have affected our estimates but urban (re-)developments and changes in travel patterns were neglectable during this three-year-long period. Second, due to the cross-sectional nature of our data, we were not able to address the causality between streetscapes and AST. Third, the measurement of travel modes relied on self-reporting, and thus some recall bias is likely (Yang et al., 2022). Fourth, we were unable to consider parental environmental perceptions and people's attitudes and preferences toward active traveling due to a lack of related data (Panter et al., 2008, Susilo and Liu, 2015). Fifth, while we addressed only active school commuting, other scholars have suggested that built environments may be differently associated with active travelling for other purposes (e.g., recreational trips) (Yang et al., 2022). Sixth, we failed to consider the environmental setting along the commuting route (Helbich et al., 2016). Seventh, as our convenience sample was relatively small, our sample may not precisely represent the target population in each neighbourhood. Finally, measurements of the three environmental perception mediators were based on single items, which were likely not accurate enough to reflect adolescents' perceived environments.

6. Conclusion

We investigated whether and to what extent the relationships between the streetscapes and adolescents' AST in Guangzhou, China, is mediated by perceived streetscape qualities. We found a higher likelihood of AST with increasing levels of safety facilities, street vitality, street greenery, vehicle volume, and lower pavement ratio. Mediation results indicated that safety facilities, pavement ratio, and vehicle volume were positively associated with a higher likelihood of AST through the enhancement of street walkability. Respondents travelling on streets with higher vitality were more likely to travel actively AST due to the increase of perceived safety and street walkability, and vehicle volume had a positive relationship with AST through the perceived air pollution-street walkability paths.

Policymakers and urban planners are advised to improve the quality of the streetscape for adolescents by prioritising pedestrians over cars. Specifically, the local government is urged to cooperate with schools to create safe travel routes. Some streets around schools are advised to be closed for vehicular traffic during morning and afternoon school commuting times. These simple interventions not only minimise the collisions risk with vehicles, but also increase pedestrians and residents' awareness of adolescents' travel safety. In addition, distribution of various types of street furniture and commercial activities were advised for shaping a vibrant street and enhancing its attractiveness to adolescents, which can promote their active travel behaviours. Finally, promoting AST needs a long-term and multilevel efforts (such as policy and environmental interventions, educational programs and so on) to not only make the streets more walkable, but also make children and adolescents more willing to choose the active travel modes over alternative passive transport modes.

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Consent for publication

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Availability of data and materials

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CRediT authorship contribution statement

Xiaoge Wang: Methodology, Software, Formal analysis, Writing – original draft. **Ye Liu:** Conceptualization, Writing – review & editing, Funding acquisition. **Yao Yao:** Data curation, Writing – review & editing. **Suhong Zhou:** Data curation, Writing – review & editing. **Qia Zhu:** Data curation. **Mingyang Liu:** Data curation. **Marco Helbich:** Writing – review & editing.

Declaration of Competing Interest

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

Appendix A. Supplementary data

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