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The activity space and the 15-minute neighborhood: An empirical study using big data in Qingdao, China

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Abstract: Daily travel distance in urban China has substantially increased. The spatial layout of the 15-minute neighborhood, which supports local living and encourages walking and biking, was detailed in the Urban Residential District Planning and Design Standards in China in 2018. This study investigates the impacts of the 15-minute neighborhood described in the 2018 standards on activity space, using mobile network data in Qingdao, China. A total of 42,991 subscribers of China Mobile are randomly sampled. The 15-minute neighborhood attributes are objectively measured for sampled residents individually. Our study shows that not all 15-minute neighborhood attributes are associated with smaller activity space. Commercial retail services and green open space, which were found to increase walking and physical activity, do not reduce activity space. On the other hand, public services such as primary school and middle school, bus stops, neighborhood centers, and sports facilities within walking distance are positively associated with smaller activity space.

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1 Introduction

Daily travel distance in many Chinese cities has substantially increased (Feng et al., 2017; Zhao, 2010) as a result of considerable urban expansion since the 1990s (Li et al., 2018). At the same time, private automobile ownership has increased dramatically (Wu et al., 2016). More than two-thirds of the CO_2 emissions of urban passenger transportation in China come from private vehicle emissions (Yuan et al., 2019). To create sustainable cities and increase the quality of life, China's Ministry of Housing and Urban-Rural Development issued "The Urban Residential District Planning and Design Standards" (GB50180-2018), which detailed the spatial layouts of "15-minute neighborhood" for cities in 2018 (The Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018). The 2018 standards, which are results from multiple studies conducted in Chinese cities (Shanghai Planning and Land Resource Administration Bureau et al., 2017), provide guidelines on the spatial locations of essential daily services and land uses, such as retail stores, commercial services, restaurants, schools, and public transportation facilities. The 2018 standards are a national guideline and will be incorporated into the new municipal site development control plan, which identifies the new development's different planning parameters plot by plot, including permitted land-use type, open space, and public facilities (Rowe, 2011; Tian & Shen, 2011).

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A growing number of city leaders worldwide have embraced the 15-minute neighborhood (C40 Cities Climate Leadership Group & C40 Knowledge Hub, 2020). The mayor of Paris won re-election by campaigning for a "15-minute city" (O'Sullivan & Bliss, 2020). Planners in Melbourne put the "20-minute neighborhoods" in their city plan (Department of Environment, Land, Water and Planning, 2018). Singapore explicitly stated creating "20-minute town and a 45-minute city" in their "Land Transport Master Plan 2040" (Land Transport Authority of Singapore, 2019).

The concept of a 15-minute neighborhood, which structures the temporal dimension into places, represents the time-space routines of everydayness (Moreno et al., 2021; Mulíček et al., 2015). Derived from the ideas of walkable neighborhoods (Moreno et al., 2021; Moudon et al., 2006; Talen & Koschinsky, 2013) and consistent with the principles of compact development (Bibri et al., 2020; Burton et al., 2003; Dantzig & Saaty, 1973), a 15-minute neighborhood supports local living and encourages walking and biking.

We hypothesize that the 15-minute neighborhood could reduce urban residents' activity space, a spatiotemporal construct that captures individual everyday routine activity locations (Cagney et al., 2020; Ren, 2016). It is believed that people are more likely to travel on foot or by bike for a short distance (Cervero & Kockelman, 1997; Ewing & Cervero, 2001; Næss, 2006). Hence, if daily routine activity locations are spatially concentrated, such as within a 15-minute neighborhood, residents are more likely to walk and bike, resulting in a smaller activity space. A few studies have examined the impacts of walkable neighborhoods and compact development on residents' activity space created by using multiple days of GPS data (Lo & Houston, 2018; Tribby et al., 2015). Meanwhile, with a high prevalence of mobile phone users worldwide, activity space has been increasingly investigated using multiple months or even year-round mobile telecommunication network data which could more accurately capture people's travel patterns (Chin et al., 2019; Järv et al., 2014). This study seeks to fill the research gap by investigating the associations impacts of the 15-minute neighborhood indicators defined in Qingdao, China on with activity space using mobile network data.

2 Literature review

Numerous previous studies have investigated the impacts of the walkable neighborhood and compact development on travel behavior (Alfonzo et al., 2014; Freeman et al., 2013; Saelens et al., 2003; Stevens, 2017; Sundquist et al., 2011). Built environmental attributes that support and encourage walking and biking were identified at the neighborhood level for different age groups. Access to bus stops, convenience stores, and transit stations within 400 meters from residents' homes were found to contribute to more walking in a Western Australian study (McCormack et al., 2008). Proximity to parks and density of bus stops from residents' homes contributed to more active travel in a US city (Tao et al., 2020). Proximity to school was associated with the active commute to school in Shanghai, China (Lin & He, 2020). For seniors in China, home proximity to a fresh local market, park/public square, and chess/card room strongly influenced their active travel (Cheng et al., 2019).

Systematic literature reviews showed that compact development reduced driving (Ewing & Cervero, 2017; Stevens, 2017). A recent study in Sweden found that an increasing number of amenities near residents' homes could mean shorter travel distances and make more people give up driving and take up walking and cycling (Elldér, 2020). However, limited studies examined the impacts of the walkable neighborhood and compact development on residents' activity space covering daily routine activity locations.

Activity space has been used before in urban mobility studies (Patterson & Farber 2015; Rai et al. 2007). Aerial coverage, frequently measured as standard deviational ellipse (SDE), could be used to rep-

resent and measure an individual's use of space (Schönfelder & Axhausen, 2016). Traditional approaches to derive activity space depended upon activity surveys or travel diaries (Li & Tong, 2016), which are costly to collect and rely on respondents' memories to recall activities. With the ubiquity of mobile phones, mobile telecommunication network data can be automatically recorded by network operators without any effort from end-users and are therefore cost-effective to produce an unlimited sample size over a long study period and to cover a large study area (Järv et al., 2014). Network data such as cellular signaling data and call detail records have been used to study individuals' spatial behavior (Chin et al., 2019; Järv et al., 2014) and in regional studies (Zhang et al., 2020). The advantages of this study are in using mobile data to objectively understand urban residents' activity space and using up-to-date commercial digital mapping data to locate the daily amenities of the 15-minute neighborhood spatially. The findings of this study could provide a more nuanced understanding of the associations between neighborhood built environment and travel behavior of urban residents.

3 Methods and data

3.1 Study area and research subjects

Qingdao, located in the north part of China, has a population of 9.5 million with a land area of 11,293 km² covering seven urban districts and three county-level cities (Qingdao Municipal Statistics Bureau & NBS Survey Office in Qingdao, 2020). China Mobile subscribers in Qingdao are randomly sampled from traffic analysis zones (TAZs) with more than 5% of the land that is designated for residential uses (Figure 1). China Mobile accounts for 65% of the market share for cell phone services in Qingdao (Wang et al., 2019). Mobile cellular signaling data, which includes information such as the Mobile Subscriber Identification Number (MSIN), the location coordinates of a cell tower, and the time stamps of arrival and leaving of a cell tower, between July 2019 and September 2019 are used to create individual activity spaces. The Mobile cellular signaling data are recorded every minute on average. Given the high density of cell towers in Qingdao, with 93% of cell towers within 200 meters from each other (Wang et al., 2019), even short-distance travels will be detected accurately.

3.2 Activity location identification, home and work location identification, and activity space creation

Activity locations are identified if a mobile signal has stayed in a place for more than 10 minutes. Sampled subscribers' home and work locations are identified using similar methods to those described in the Isaacman et al. study (2011). Specifically, "home" hours are defined as between 12 am and 8 am on weekdays and weekends, whereas "work" hours are between 9 am and 6 pm during weekdays. Each cluster is calculated and ranked based on frequencies, durations, and clustering locations during work hours and home hours. The cluster with the highest frequency and longest duration during home hours is identified as home location. The cluster with the highest frequency and longest duration during work hours is considered a workplace. Two standard deviational ellipses (SDE) that capture 95% of the activity locations (Patterson & Farber, 2015) are used to generate the activity spaces of sampled mobile phone subscribers.

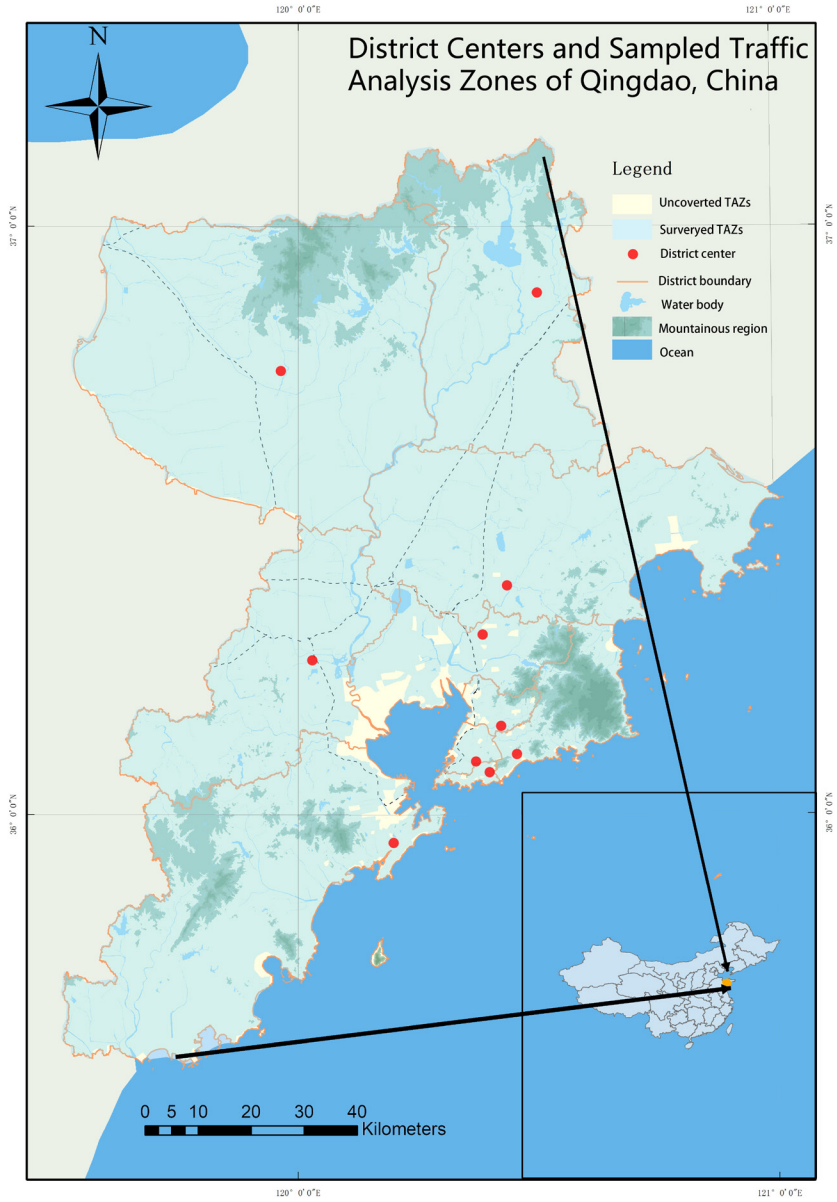

Figure 1. District centers and sampled traffic analysis zones of Qingdao, Shandong, China

3.3 The 15-minute neighborhood

The 15-minute neighborhood attributes described in the 2018 standards are measured using the application programming interface (API) of AutoNavi, a Chinese commercial web mapping, navigation, and location-based services platform. Specifically, the 2018 standards state that within a 5-minute walk or 300 meters, there should be a kindergarten, a convenience store, and at least 4,000 m² of green open space. Within a 10-minute walk or 500 meters, there should be a primary school, a farmer's market, a restaurant, and a bus stop. Within a 15-minute walk or 800 meters, there should be a middle school, a supermarket, a neighborhood public service center, and a sports facility. It should note that the 2018 standards represent an ideal spatial layout of a 15-minute neighborhood and not all the items described in the standards are mandatory. Furthermore, no previous studies have concluded how many conve-

nience stores within a 5-minute walking distance from home should have in a 15-minute or walkable neighborhood. Therefore, this study only counts whether there are certain facilities and services within the 300 meters, 500 meters, and 800 meters from a sampled home, respectively. Table 1 summarizes the measurements of the 15-minute neighborhood attributes. Points of interest (POI) data from AutoNavi are used to measure the services included in the 15-minute neighborhood. Green open space coverage is measured using the Third National Land Survey (Luo et al., 2020; Xinhua, 2017).

Table 1. The "15-minute neighborhood" attributes described in the 2018 standards (GB50180-2018)

	Attribute	Measurement	Data source
5 minutes walking distance from home (300 meters)	Kindergarten	Counts	AutoNavi POI
	Convenience store	Counts	AutoNavi POI
	Green open space coverage	Area	The Third National Land Survey
10 minutes walking distance from home (500 meters)	Primary school	Counts	AutoNavi POI
	Farmer's market	Counts	AutoNavi POI
	Restaurant	Counts	AutoNavi POI
	Bus stop	Counts	AutoNavi POI
15 minutes walking distance from home (800 meters)	Middle school	Counts	AutoNavi POI
	Supermarket	Counts	AutoNavi POI
	Neighborhood public service center	Counts	AutoNavi POI
	Sports facility	Counts	AutoNavi POI

3.4 Socio-demographic information at Traffic Analysis Zone (TAZ) level

The socio-demographic information at TAZ, defined by the Department of Transportation of Qingdao, was estimated based on the Third Travel Survey of Qingdao in 2017. With a total of 297,000 valid surveys, the Third Travel Survey of Qingdao oversampled residents aged between 18 and 44 years old and accounted for 3% of the total population in Qingdao (Wang et al., 2017).

3.5 Statistical analysis

A linear mixed-effects model is developed to investigate the associations of 15-minute neighborhood attributes and activity space. Even though recent physical activity studies found non-linear built environment effects on walking (Christiansen et al., 2016; Lu et al., 2019; Yang et al., 2022), studies on travel behaviors on driving and activity space showed linear associations between the built environment and activity space (Chen et al., 2017; Zhao et al., 2020). Hence, a linear model is employed in this study. To address spatial autocorrelation, the Euclidean distance from a sampled subscriber's home to the closest district center is included in the fixed effect as the autocovariate (Dormann et al., 2007), which is an indicator of an endogenous process where distance is inversely associated with being located in a district center. As the mobile cellular signaling data do not have individual socio-demographic information, we assign socio-demographic information at the TAZ to the individual level. At the same time, TAZs are included in the random effect to account for the within-group variance and address the unobserved heterogeneity problem.

The model specification for the random intercept regression model is below.

$$\ln y_{ij} = b_0 + b_1 X_{ij} + v_i + e_{ij}$$

for $i \in \{1,...,1240\}$ (TAZ) and $j \in \{1,...,42,991\}$ (sampled mobile subscribers) where
y_{ij} indicates sampled mobile subscriber's activity space (area in m²)
b_0 indicates the fixed intercept
b_1 indicates the fixed slopes
X_{ij} indicates predictors of the fixed effects, which include 15-minute neighborhood attributes, Euclidean distance from home to the closest district center (natural logged transformed), and socio-demographic characteristics of TAZs
$v_i \sim N(0, \sigma_v^2)$ is the random intercept for the i-th subject
$e_{ij} \sim N(0, \sigma_v^2)$ is a Gaussian error term

4 Results

A total of 42,991 subscribers of China Mobile are randomly sampled from 1240 TAZs in Qingdao, China, which covers 66% of the municipality's territories and 82.1% of the urban area. Table 2 summarizes the results of the descriptive statistics of activity space, 15-minute neighborhood attributes, and distance from sampled residents' homes to the closest district centers. A resident's average activity space is 2,263 KM² (SD: 2,481.7). The attributes of the 15-minute neighborhood are measured for all the sampled residents. Within 5 minutes walking distance from a resident's home, slightly less than half of the sampled residents have a kindergarten, about two-thirds have a convenience store, and about one-fourth have green open space less than the minimum recommended 4,000m² within the 300-meter buffer. Within 10 minutes of walking distance, about 16% of sampled residents have a primary school, 67.7% have a farmer's market, 86% have at least one restaurant, and 85.8% have at least one bus stop. Within 15 minutes of walking distance, 36.9% of the sampled residents have a middle school, more than 90% have a supermarket, 56.8% have a neighborhood public service center, and more than 70% have sports facilities. However, only 3.1% (1,317) of residents' homes include all recommended facilities and services from the 2018 standards.

Table 2. Descriptive statistics of the "15-minute neighborhood" attributes for 42,991 sampled residents in Qingdao, China

		Attribute	Mean (SD)/Frequency
Activity space (dependent variable)		area in m²	2,263,001,906.69±2,481,701,354.51
		natural log-transformed	20.91±1.30
15-minute neighborhood attributes (independent variables)	5 minutes walking distance from home	Kindergarten	Yes: 19,940 (46.4%) No: 23,051 (53.6%)
		Convenience store	Yes: 28,580 (66.5%) No: 14,411 (33.5%)
		Green open space coverage	Less than 4000 m²: 11,765(27.4%) 4000 m² and more: 31,226 (72.6%)
	10 minutes walking distance from home	Primary school	Yes: 6,941 (16.1%) No: 36,050 (83.9%)
		Farmer's market	Yes: 29,113 (67.7%) No: 13,878 (32.3%)
		Restaurant	Yes: 36,960 (86.0%) No: 6,031 (14.0%)
		Bus stop	Yes: 36,877 (85.8%) No: 6,114 (14.2%)
	15 minutes walking distance from home	Middle school	Yes: 15,862 (36.9%) No: 27,129 (63.1%)
		Supermarket	Yes: 39,176 (91.1%) No: 3,815 (8.9%)
		Neighborhood public service center	Yes: 24,435 (56.8%) No: 18,556 (43.2%)
		Sports facility	Yes: 30,359 (70.6%) No: 12,632 (29.4%)
Distance (in meter) (independent variable)		Euclidean distance from home to the closest district center	8,369.02 (8,705.93)
		Euclidean distance from home to work	8,362.59 (150,925.14)

The average distances from home to the closest district center and from home to work are 8.4 km. Furthermore, those 15-minute neighborhoods are located on an average of 3 km from a district center (data not shown). It should be noted that more than 50% (21,894) of the sampled resident's work locations could not be identified from the mobile signal data.

The physical and socio-demographic characteristics of sampled 1,240 TAZs are summarized in Table 3. The average size of a TAZ is 6.03 km², the average population is 7,555 persons, and the average population density is 10,301 persons per km². There are 35 individuals sampled in a TAZ on average. As for the socio-demographic characteristics of TAZs, a TAZ, on average, has about 55% male residents, about 82% residents aged between 18 and 44 years old, about 63% with education up to high schools, and approximately one in five with a private car. The average monthly income per person is 4,378 RMB for a TAZ.

Table 3. Descriptive statistics of TAZs

	Attribute	Mean (SD)
Physical characteristics of TAZs	Sampled subscribers in a TAZ	35±34.00
	TAZ Area in KM²	6.03±30.06
	Estimated number of residents in a TAZ	7,554.91±7,989.97
	Population density (people/km²) in a TAZ	10,301.57±12,181.35
Socio-demographic characteristics of TAZs (independent variables)	percentage of residents are men	55.38%±5.73%
	Percentage of residents aged between 18 and 44 years old	81.96%±6.21%
	percentage of residents with up to high school degree	62.92%±13.42%
	percentage of residents with cars	21.10%±4.00%
	Average monthly income (RMB)	4,378.07±954.07

The fixed effect results of the mixed model are summarized in Table 4. Primary schools, bus stops, middle schools, neighborhood service centers, and sports facilities are significantly associated with activity space. Specifically, residents with primary schools and bus stops within a 10-minute walk of their home would have significantly smaller activity space compared with their counterparts without these two attributes. Similarly, residents with middle schools, neighborhood service centers, and sports facilities within a 15-minute walk of their home would have significantly smaller activity space than their counterparts who do not have those attributes.

As for the socio-demographic attributes, if a resident lives in a TAZ with a higher percentage of men, they would have significantly smaller activity space. TAZs with a higher rate of residents aged between 18 and 44 years old, and a higher percentage of residents with up to high school degrees are significantly positively associated with activity space. TAZs with higher monthly income also positively contribute to activity space. Euclidean distance from home to the closest district center is significantly and positively associated with activity space.

Table 4. Fixed effect results

				Fixed effect	
				B	p-value
		intercept		**18.623**	**<0.001**
		Euclidean distance from home to the closest district center (natural logged transformed)		**0.076**	**<0.001**
15-minute neighborhood attributes	5 minutes walking distance from home	Kindergarten	No	0.004	0.811
			Yes#	0.000	
		Convenience store	No	0,025	0.172
			Yes#	0.000	
		Green space	Less than 4000m²	-0.013	0.425
			4000m² and above #	0.000	
	10 minutes walking distance from home	Primary school	No	**0.066**	**<0.001**
			Yes#	0.000	
		Farmer's market	No	-0.013	0.517
			Yes#	0.000	
		restaurants	No	0.027	0.314
			Yes#	0.000	
		Bus stops	No	**0.077**	**<0.001**
			Yes#	0.000	
	15 minutes walking distance from home	Middle school	No	**0.064**	**<0.001**
			Yes#	0.000	
		Supermarket	No	0.043	0.144
			Yes#	0.000	
		Neighborhood public service center	No	**0.117**	**<0.001**
			Yes#	0.000	
		Sports facility	No	**0.040**	**0.050**
			Yes#	0.000	
Socio-demographic characteristics of TAZs	Percentage of residents is men			**-0.004**	**0.023**
	Percentage of residents aged between 18 and 44 years old			**0.011**	**<0.001**
	percentage of residents with up to high school degree			**0.005**	**0.018**
	percentage of residents with cars			0.003	0.164
	average monthly income in a TAZ in 1000 RMB			**0.087**	**0.003**
				Random effect	
	Intercept			**0.026**	**<0.001**

Dependent variable: activity space (two SDEs)
: reference category
Bolded indicate p-value <0.05

5 Discussion

5.1 5-minute neighborhood

The neighborhood is theoretically defined by home and everyday activities (Chaskin, 1997; Galster, 2001; Moudon et al., 2006). Surprisingly, only 3.1% of residents' homes in Qingdao are located within neighborhoods that include all recommended facilities and services from the 2018 standards. With an average distance of 3 km from a district center, those 15-minute neighborhoods tend to cluster around district centers.

The tallying of facilities and services shows that the most considerable improvement needed in Qingdao is with primary schools, with only 16% of residents having a primary school within a 10-minute walk from their homes. Slightly more than half of the residents have a kindergarten within the recommended 5-minute walking distance, and more than one third have a middle school within 15 minutes walking distance. It is interesting to note that kindergarten within 5 minutes of walking distance from home did not reduce activity space. It is the presence of primary and middle schools that could significantly reduce urban residents' activity space. Limited studies investigated the impacts of school distance on other household members' travel patterns. Our current research suggests that primary and middle schools located within walkable distances could positively reduce adult household members' travel.

It is believed that people are more likely to travel on foot or by bike for a short distance (Cervero & Kockelman, 1997; Ewing & Cervero, 2001; Næss, 2006). Hence, if daily routine activity locations are spatially concentrated, residents are more likely to walk and bike. Subsequently, we hypothesized that the 15-minute neighborhood attributes could reduce urban residents' activity space. Between 66% to 90% of residents in Qingdao have commercial retail services such as convenience stores within 5 minutes walking distance, farmer's markets and restaurants within 10 minutes walking distance, and a supermarket within 15 minutes walking distance of their homes. However, those commercial retail services were found to be significantly associated with more walking and physical activities in previous studies (Gunn et al., 2017; McCormack et al., 2008; Moudon et al., 2006; Yang & Diez-Roux, 2012), but these did not show a considerable reduction in activity space in our study. As for green open space, most residents do not have the minimum recommended 4,000 m² within 5 minutes walking distance around their homes. Interestingly, green open space is not found to reduce activity space significantly. Previous studies have found that access to green open space could increase physical activity, including walking (Mytton et al., 2012; Wang et al., 2019). This result indicates that more walking trips might not guarantee smaller activity space.

Transportation facilities such as bus stops within 10 minutes walking distance from residents' homes also have a high prevalence in Qingdao. Additionally, the regression analysis confirmed that bus stops reduce activity space significantly. This is consistent with an Australian study that access to bus stops within 400 meters from residents' homes could increase walking (McCormack et al., 2008).

Neighborhood public service centers that provide community public services within 15 minutes walking distance from home could significantly reduce residents' activity space. About 43% of sampled individuals do not have a neighborhood public service center within 15 minutes walking distance from their homes in Qingdao, which indicates that substantial neighborhood public service centers need to be created.

Our research shows that sports facilities within 15 minutes walking distance from home could reduce activity space, which is consistent with the findings of previous studies that positive associations between the accessibility of sports facilities and physical activity were observed across countries and age groups (Halonen et al., 2015; Lee et al., 2016 ; Prins et al., 2009 ; Reimers et al., 2014). With more than 70% of residents having sports facilities within 15 minutes of walking distance, residents in Qingdao have good access to sports facilities.

It should be noted that we measured the 15-minute neighborhood attributes centered on the resident's home. In other words, if two residents live in the same residential complex but different buildings, their 15-minute neighborhood attributes could be significantly different. However, the 2018 standards do not provide clear instructions on where the 15-minute neighborhood should be centered. As a result, implementations of the standards will depend on the interpretations of local planners and developers.

5.2 Activity space

Few other cities or regions have carried out similar studies to compare residents' activity space generated by mobile phone signal data, with Estonia being an exception (Järv et al., 2014). Qingdao residents' activity space is 2,263 km² on average with the three-month span of available data, which is smaller than the residents' activity space in Estonia with an average of 2,913 km² over a month. It is noted that more than half of the sampled individual's work locations were not identified from the mobile signal data, which might indicate that more than half of residents do not have a fixed work location. Those residents could deliver packages or food or drive shared cars. They could live where they work or be unemployed.

The regression results of proxy measures of socio-demographic attributes suggest that people who live in a TAZ with higher percentages of women, people aged between 18 and 44, and people with lower education are more likely to have bigger activity space than their counterparts. Residents who live in a TAZ with a higher average monthly income are found to be associated with bigger activity spaces. However, as socio-demographic attributes are not at the individual level due to privacy concerns, our study results on socio-demographic characteristics at the TAZ level should be interpreted with cautions.

5.3 Limitations

Due to privacy concerns, no individual socio-demographic information was available for the mobile phone data. We substituted with socio-demographic characteristics of TAZs calculated based on the Third Travel Survey of Qingdao in 2017. This could result in a possible ecological fallacy. Home and work locations were estimated based on mobile phone data for staying in the same locations for a fixed number of hours. This approach could not capture residents who do not have fixed work locations, work from home, or are unemployed or retired. Activity space was calculated using three months' mobile phone data, as a result not all activity locations were frequently visited. Future studies could calculate activity space based on frequently visited activity locations. We assumed that the activity space of residents with more walking and biking trips would be smaller than their counterparts. Studies need to be carried out to confirm this assumption.

6 Conclusions

Our study shows that not all 15-minute neighborhood attributes included in the 2018 standards are associated with smaller activity space. Commercial retail services and green open space that are found to increase walking and physical activity do not reduce activity space. On the other hand, public services such as primary school and middle school, bus stops, neighborhood centers, and sports facilities within walking distance could significantly reduce activity space.

The 15-minute neighborhood concept will be interpreted and implemented from place to place. Our results start to offer insights on how 15-minute neighborhood attributes could impact residents' daily travel and show evidence for policy making on prioritizing public services.

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