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Neighborhood effects on health: A multilevel analysis of neighborhood environment, physical activity and public health in suburban Shanghai

Yinhua Tao [a], Jing Ma [b,*], Yue Shen [c], Yanwei Chai [d]

[a] Faculty of Architecture and the Built Environment, Delft University of Technology, 2628 BL Delft, the Netherlands
[b] Beijing Key Laboratory for Remote Sensing of Environment and Digital Cities, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[c] School of Urban and Regional Science, East China Normal University, Shanghai 200062, China
[d] College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

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ABSTRACT

With great concern over the health-promoting environment worldwide, there is a growing body of research into the neighborhood effects on health beyond the sole focus on individual socioeconomic disadvantages and lifestyle risks. Our study contributes to neighborhood health research by investigating the combined effects of multidimensional neighborhood environmental characteristics and recreational physical activity under different geographic contexts on residents' self-rated health. Drawing upon a health survey conducted in suburban Shanghai in 2017, we employ a series of multilevel models to examine how the multi-scale environmental and behavioral factors are related to residents' self-rated physical and mental health, respectively. The results show that the greening rate of the community, rather than accessibility to large-scale urban parks, is a significant indicator of self-rated health for suburban residents. Subjective evaluations on neighborhood safety and air pollution exposure are significantly associated with residents' physical and mental health, while neighborhood attachment matters more for mental health. Outdoor recreational exercises, especially in the environment of neighborhood green space, are conducive to better physical health, while indoor physical activity shows weaker and insignificant health benefits. These findings offer a promising way for public health policymakers and urban planners to implement place-based health interventions and develop health-supportive neighborhoods.

1. Introduction

Rapid urbanization with associated environmental and behavioral risks are posing great risks to public health. It is estimated that non-communicable diseases (NCDs) have become the leading threats to physical health, with >5 million deaths per year attributable to unhealthy diet, road injuries, and physical inactivity (Sallis et al., 2016). Also, mental health problems are increasingly prevalent for urban populations, with one in every five people obsessed with mental disorders, such as depression and anxiety (Jackson et al., 2013; Yang et al., 2013). Considering that one-third of these health problems can be ascribed to the environment- or behavior-related risk factors, World Health Organization (World Health Organization, 2016) puts forward that developing a health-promoting neighborhood environment is an important task for urban administrators and practitioners. This task foregrounds a research need to comprehensively understand the relationships among neighborhood environment, health-related behaviors and health outcomes.

Socio-ecological models ascribe the determinants of population health to multilevel components, including the microsystem of intra- and inter-individual factors, the mesosystem of immediate community contexts, and the macrosystem of socio-institutional backgrounds (McLeroy et al., 1988; Sallis et al., 2006; Stokols, 1996). This socio-ecological perspective moves beyond the health effect of individual-level lifestyle risks to understand the structural characteristics of places in shaping people's health outcomes (Shen & Tao, 2022). Neighborhood effects, as a part of the mesosystem of socio-ecological models, are increasingly studied by urban researchers and health geographers because of the contextual perspective on health determinants and the relevance to place-based health interventions (Diez Roux & Mair, 2010). A growing body of studies have examined how different dimensions of neighborhood environment, including built environment, environmental pollution, and social environment, are independently associated with individual physical and mental health after controlling for the

* Corresponding author.
E-mail address: majingbnu@163.com (J. Ma).

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effect of individual socioeconomic characteristics (e.g., Christian et al., 2011; Craveiro, 2017; Hooper et al., 2018; Ma, Li, et al., 2020; Tao et al., 2019). Besides, some planning practices have been implemented in cities of developed countries, such as the Project on Human Development in Chicago Neighborhoods (Sampson, 2012), Liveable Neighborhoods in Western Australia (Giles-Corti et al., 2013), and Neighborhood Effects on Health and Well-being in Toronto (Wheaton et al., 2015). Other neighborhood intervention projects also place the improvement of public health and well-being as a secondary target, such as the HOPE VI (Popkin & Cunningham, 2009) and the Moving to Opportunity (Jackson et al., 2009) in the United States, and Neighborhood Effects and the DEPRIVEHOODS in the United Kingdom and the Netherlands (van Ham et al., 2021).

Physical activity is well-documented as an behavioral moderator in neighborhood effects on health. Specific to different domains of physical activity, evidence on transport-related physical activity is relatively consistent that a walkable and compact neighborhood environment encourages frequent active travels and thus produces significant health benefits (e.g., Christian et al., 2011; Ewing & Cervero, 2010; Shen et al., 2021). However, research on the health effects of recreational physical activity is less conclusive. The reason may be that exercises for leisure depend on the proximity to and attractiveness of activity sites in the living space while exercises in specific geographic contexts are to a varying degree related to health outcomes (Maas et al., 2008; Puett et al., 2014). For instance, outdoor recreational exercises in a green environment should have been good for health, but ambient air pollutants would increase people's exposure to environmental hazards and might counteract the health benefit of green exposure (Giallouros et al., 2020).

Notably, neighborhood health research is dominated by the evidence from developed countries. In cities of the developing world, however, the role of neighborhood on health is under-researched. Different from North America and some European countries where low-density urban sprawl is driven by thriving automobile industries and changes in middle-class lifestyles for better living environment, suburbanization in Chinese megacities follows more complicated socio-spatial patterns in terms of the suburban relocation of populations and industries (Zhao, 2011; Zhou & Ma, 2000). Apart from the middle-income populations relocating to newly-built commercial housing neighborhoods, there are other forms of population suburbanization, such as in-situ suburbanization of former rural populations and forced relocation of inner-city residents, which shape diverse types of neighborhoods and neighborhood environments in the suburb (Zhao & Li, 2018; Li et al., 2021). In addition, the industrial decentralization policy relocates manufacturing industries and massive infrastructure constructions to the suburb, resulting in serious noise and air pollution issues (Holdaway, 2010; Ma, Tao, et al., 2020). Meanwhile, the labor-intensive tertiary industry still concentrates in the inner city. Many suburban residents have to endure long job-housing distance, which poses great spatiotemporal constraints on their social contacts and recreational exercises in the neighborhood (Shen et al., 2021). In general, the unique socio-spatial context of suburban China deserves great concern in the research of neighborhood effects on health.

Our study draws upon health survey data and multilevel models to investigate the relationships among neighborhood environment, physical activity and public health in rapidly suburbanizing Shanghai, China. Specifically, two research questions are included in our study: 1) To what extent different dimensions of neighborhood environment are associated with residents' self-rated physical and mental health after controlling for individual socioeconomic characteristics; 2) Whether outdoor and indoor exercises for leisure are similarly related to self-rated health, and if not, how the outdoor exercises moderate the associations of neighborhood environmental benefits (e.g., green space) and risks (e.g., air pollution) with health. Our study contributes to the international evidence on neighborhood effects on health in three aspects. First, we go beyond the single dimension of neighborhood environment to examine the combined health effect of multidimensional neighborhood environments, including built environment, environmental pollution, and social environment. Second, we differentiate the geographic contexts of recreational physical activity (i.e., indoors and outdoors) and further estimate the health effect of outdoor exercises performed in the green and air-polluted neighborhood environment. Third, we select diverse types of neighborhoods in suburban Shanghai as the case to reflect on how suburbanization drives great environmental and health risks in cities of China and beyond.

2. Literature review

2.1. Neighborhood environment and health

Neighborhood effects are a notion of great concern in understanding the place-health nexus. Over the past decades, there is a growing body of research investigating the neighborhood effects on health (see reviews by Diez Roux & Mair, 2010, Oakes et al., 2015, and Arcaya et al., 2016), involving the debate on composition (i.e., individual-level socioeconomic compositions and lifestyles) versus context (i.e., physical and social environment that individuals are exposed to) as the determinants of health (Duncan et al., 1998; Petrović et al., 2020). Prevailing evidence shows that individual-level explanations fail to capture the wider environmental opportunities and constraints in people's living space, while neighborhoods do exert an independent effect on individual behavioral and health outcomes through the socio-interactive, environmental, geographical and institutional mechanisms (van Ham et al., 2012). Moreover, the contextual explanations on determinants of health are justified by the policy relevance to implementing place-based interventions in promoting population health (Diez Roux & Mair, 2010).

However, embracing the neighborhood effects and contextual perspective on health determinants still involves several theoretical and methodological issues. The first issue is how to define and operationalize the neighborhood that is contextually relevant to health. Most previous studies draw upon census-defined areas (e.g., census tracts or blocks in the United States and wards in the United Kingdom) to delineate the neighborhood boundary and link the contextual exposure within the boundary to the health outcomes (e.g., Arcaya et al., 2016; Carlson et al., 2012). This administrative-based delineation of a neighborhood has been greatly criticized because it can only be justified by the operational convenience, i.e., the data availability in the census area, rather than represent any theoretically sound spatial scale underlying the process of how contextual neighborhoods shape and reshape individual health (Kwan, 2018; Petrović et al., 2020).

Another important issue is how to measure the multidimensional contexts of a neighborhood given that these dimensions are interrelated with each other and may have a combined effect on health. Broadly, contextual neighborhood environment can be divided into physical environment and social environment (Diez Roux & Mair, 2010). To date, evidence is consistent in the health benefits of compact, walkable, and green neighborhood built environment. Specifically, densely-populated, mixed-use and pedestrian-oriented neighborhoods create a vibrant and pleasant environment beneficial to people's health and well-being (e.g., Hooper et al., 2018; Jackson et al., 2013; Tao et al., 2019). In addition, abundant green space in the living space not only helps to filter hazardous pollutants and reduce the risks of respiratory diseases and heart-related diseases, but also provides opportunities for health-related behaviors, such as social contacts and recreational activities, in the natural environment (Liu et al., 2020; Qin et al., 2021; Wolch et al., 2014). Environmental pollution, the other component of physical environment, has received increasing attention in developing countries where serious environmental pollution subjects people to significant health risks. Some review articles demonstrate that long-term exposure to air pollution is linked to the morbidity of asthma, stroke, lung cancer, cardiovascular diseases (Hoek et al., 2013; Shah et al., 2013), and mental disorders (Braithwaite et al., 2019; Tao et al., 2021). In addition, noise pollution also has detrimental effects on hypertension, sleep disturbance and psychological stress (Ma, Li, et al., 2020; Tao et al., 2020).

Compared with the health effect of physical environment, the role of social environment is less investigated although it is often framed as a pathway for neighborhood effects on health (see reviews by Pickett & Pearl, 2001, and Diez Roux & Mair, 2010). Social environment, by definition, is a proxy for residents' subjective evaluations on social interactions with neighbors, the presence of social norms, and the levels of neighborhood safety and attachment (Diez Roux & Mair, 2010). Emerging evidence shows that residents who do not feel safe in the neighborhood would conduct fewer outdoor activities, have less social contact, and report worse health status (Christian et al., 2011; Leslie & Cerin, 2008; Tao et al., 2019). In contrast, frequent communications with neighbors and strong neighborhood attachment provide solid emotional support and build resilience to physical and mental health problems (Craveiro, 2017).

To summarize, previous neighborhood health research often regards physical and social constructs of neighborhood environment as two independent dimensions, which overlooks their interaction over space and the combined effect on public health. It has been found that the joint analysis of physical and social environment has better performances in goodness-of-fit statistics and provides a better understanding of environmental determinants of health (McGinn et al., 2007). For instance, activities in outdoor green space might subject residents to serious environmental pollution, so the health gains of green space could be reduced or even reversed (Giallouros et al., 2020; Wolch et al., 2014). This is particularly the case in developing megacities where the rapid expansion of urban physical space and restructuring of urban industrial and social space are underway with multiple environmental and health risks (Shen et al., 2021).

2.2. Physical activity and health

Physical activity and its health effects are domain specific. Evidence has indicated the health benefits of transport-related physical activity on reducing body mass index and alleviating mental disorders (Christian et al., 2011; Ewing & Cervero, 2010; Koohsari et al., 2013; Shen et al., 2021). However, the findings for other domains of physical activity (e.g., recreational exercises) are limited and inconsistent. The review research by Penedo and Dahn (2005) suggests that exercises for leisure contribute to reducing the morbidity of some diseases (e.g., obesity, cardiovascular diseases and anxiety), while other research indicates that the health benefit of recreational physical activity could be weak or even negligible, depending on the specific context where and when the exercises take place (Maas et al., 2008; Rütten et al., 2001).

Compared with transport-related physical activity, recreational exercises are more contingent on the provision of activity sites in the neighborhood, where the specific contextual exposure might play a role in influencing the health effect of recreational exercises. Much literature exists to show that accessible green space around the home location is an appealing site for outdoor exercises because of the direct contact with the natural environment (Maas et al., 2008; Mitchell, 2013; Schipperijn et al., 2017). However, the sole presence of green space does not necessarily imply its actual use. For instance, a poorly maintained and wrong-scale park or public garden often fails to attract frequent recreational exercises and boost people's health performances. Evidence from the United States and Australia supports that larger green space with high-quality facilities and amenities stimulates more exercises than small-size pocket parks where sedentary forms of recreation are more prevalent (Giles-Corti et al., 2005; Kaczynski et al., 2008). Furthermore, exercises in the outdoor green environment are compounded with multiple environmental risks, so the protective and therapeutic function of physical activity may be attenuated. For example, an observational study in South California finds that the health-promoting effect of outdoor exercises in a walkable neighborhood is fully counteracted by the harmful air pollutants (Hankey et al., 2012).

To summarize, the mixed findings for the health effect of recreational physical activity could be accounted for by specific geographic contexts where the exercise takes place, i.e., indoor or outdoor places in our study. Especially in developing countries such as China, multiple environmental hazards induced by rapid industrialization and motorization could counteract the health benefits of outdoor exercises (Li et al., 2015; Schipperijn et al., 2017). Meanwhile, increasing urbanities pursue indoor exercises because of increased disposable income and available exercise facilities in the neighborhood. It is unclear, however, whether exercises in such confined indoor space produce similar health benefits as outdoor exercises.

3. Methodology

3.1. Data

Shanghai, a large and prosperous coastal city in China, has experienced rapid economic growth, urban expansion and population suburbanization for decades. By 2016, Shanghai has a population of 24 million and covers an area of 6340 km^2. Annually, there are more than half a million people moving into this megacity and mainly residing in the periphery urban areas. According to the administrative division, the districts of Shanghai can be broadly divided into urban and suburban districts, with most suburban districts located outside the outer ring road (Fig. 1).

The suburbanization of Shanghai dates from the 1990s. Since then, the establishment and development of *Pudong* New District have changed the urban spatial structure, while some other suburban districts, such as *Jiading*, *Songjiang*, *Qingpu* and *Fengxian*, have developed several new towns to facilitate the suburbanization of population and industries. Notably, this remarkable economic growth and spatial transformation are accompanied with multiple environmental and behavioral risks for suburban residents, including job-housing mismatch, weak neighborhood attachment, underdeveloped public facilities and services, and the agglomeration of manufacturing industries with serious noise and air pollution (Shen et al., 2021). These problems have posed great threats to suburban residents' health and well-being in the megacity of Shanghai.

Our study draws from an activity and health survey conducted in suburban Shanghai from April to June 2017. The survey follows a three-stage stratified sampling process. First, ten towns covering a wide range of geographic locations and economic levels were randomly selected from eight suburban administrative districts. Then, three to five residential communities from each of the ten towns were investigated to include a variety of suburban neighborhood environments (Fig. 1). Finally, in each community, residents aged 18–60 years old and living in their current residences for more than six months were randomly recruited by the apartment number to participate in the survey. The survey has been approved by the district governments of Shanghai, and the privacy of participants' information is strictly protected in accordance with the Chinese Personal Information Protection Regulations.

The activity and health survey collects information on individual socioeconomic characteristics, subjective evaluations on neighborhood environment, daily activity-travel behavior, and self-rated health status. In total, 1296 participants from 38 residential communities were initially recruited and 1174 participants completed the survey. Our study finally included 952 participants who do not have missing value for the variables of interest for analysis. Table 1 presents the socioeconomic characteristics of the studied participants. Around half of the participants are male and rural-to-urban migrants. The majority of them have full-time jobs, high-school education or above, and household income above 5000 RMB per month. Overall, the socioeonomics of the studied participants are similar to those of initially recruited participants, and are also comparable with the population structure of Shanghai according to the Sixth National Population Census in 2010, except that rural-to-urban migrants are slightly overrepresented.

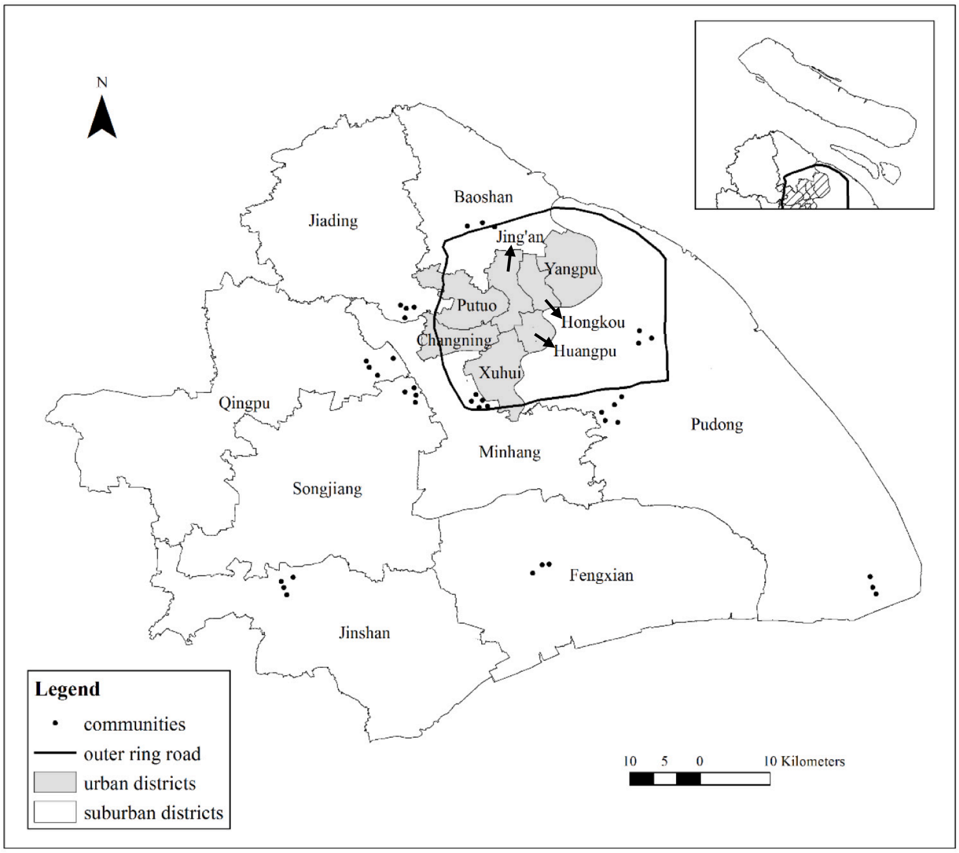

Fig. 1. Surveyed communities in the suburban districts of Shanghai.

Table 1
Key socio-economic characteristics of the studied residents ($N = 952$).

Variable	Description	N	Percentage (%)
Gender	Male	483	50.7
	Female	469	49.3
Age	18–29	223	23.4
	30–39	304	31.9
	40–49	235	24.7
	50–60	190	20.0
Residential registration status	Local residents	504	52.9
	Rural-to-urban migrants	448	47.1
Educational attainment	Middle school or below	231	24.3
	High school or college	403	42.3
	University or above	318	33.4
Employment status	Full-time employment	717	75.3
	Unemployment or others	235	24.7
Household monthly income (RMB)	Below 5000	159	16.7
	5000–10,000	374	39.3
	10,001–20,000	288	30.2
	Above 20,000	131	13.8

Note: RMB, or *renminbi*, is the official currency of People's Republic of China.

Point-of-interest (POI) data in 2017, derived from the AMAP corporation that is one of the biggest companies of digital maps in China, are employed to measure built environment characteristics for each of the 38 surveyed communities. Since the market-oriented reform of land and housing markets in Chinese cities, urban housing types are increasingly diverse across residential communities (Tao et al., 2021). Our study covers main types of communities in suburban Shanghai, including commercial housing communities, policy-related communities, mixed communities, and self-built communities (urban villages), among which policy-related communities consist of affordable housing and removal settlement housing with the housing price much lower than the market level. Table 2 presents the basic information and built environment characteristics of different types of residential communities. Compared with policy-related communities, commercial housing communities and mixed communities are greener and more densely populated, surrounded by well-connected street networks and accessible public transport and facilities, while self-built communities are particularly short of green space. Even so, residents' self-rated levels of health status are less varying among different types of communities.

3.2. Measuring physical activity

Recreational physical activity (PA) is differentiated by the indoor and outdoor contexts. Participants were required to answer the question: Every week, how many times do you undertake moderate-to-vigorous physical activity for leisure (e.g., jogging or running, gymnastics, playing sports such as football and basketball, etc.) that lasts over 30 min indoors and outdoors, respectively? If the frequency of indoor or outdoor PA is not zero, participants were further asked about the specific activity locations. Fig. 2 presents the distribution for the frequency of indoor, outdoor and total PA. 51.7 % and 34.7 % of the participants respectively participate in moderate-to-vigorous recreational PA >3 times and 5 times per week, while there are about 25 % of the participants who do not report any recreational PA for a week. Compared with indoor PA (mean = 0.92), participants prefer outdoor recreational exercises (mean = 2.34), and 38.4 % of them engage in over 30-min outdoor PA at least 3 times per week.

We also take into account transport-related physical activity that may influence people's willingness of participating in recreational exercises. Specifically, job-housing distance (the Euclidean distance from home locations to workplaces) and primary commuting mode (car,

Table 2
Basic information and built environment characteristics of different community types ($N = 38$).

	Commercial housing community	Mixed community	Policy-related community	Self-built community (urban village)
Number of surveyed communities	16	14	5	3
Average floor area (km^2)	0.15	0.09	0.05	0.02
Average number of households	1441	1698	822	200
Average number of populations for the 100 m × 100 m grid within the 1 km street network buffer	44.20	68.22	35.93	66.79
Number of road intersections within the 1 km road network buffer	48.25	59.79	33.80	34.00
Distance to the nearest rail station (km)	2.86	8.90	3.31	1.09
Distance to the nearest urban park (km)	1.06	1.69	1.55	1.61
Distance to the nearest indoor gym (km)	0.39	0.59	0.66	0.28
Number of shops within the 1 km street network buffer	343.06	340.05	232.40	354.00
The greening rate of the community (%)	39.31	37.79	35.40	28.33
Self-rated physical health as (very) good (%)	74.8	73.5	76.6	78.7
Self-rated mental health as (very) good (%)	80.7	79.5	76.6	87.2

public transport, and active mode including walk and bicycle) are included to account for the arduous commuting journeys for many working populations in suburban areas. In addition, travel satisfaction is considered as a coarse proxy for the experienced utility of people's daily travels, which is measured by the question: What is your overall evaluation on daily travels? Answers are quantified from 1 (very unsatisfied) to 5 (very satisfied).

3.3. Measuring neighborhood environment

Three subsets of variables are used to delineate neighborhood environment, namely built environment, environmental pollution, and social environment (Table 3). Specifically, built environment characteristics concerning people's health and physical activity are included. They are population density, street connectivity, accessibility to indoor gyms and urban parks, and the greening rate of the community. These variables are calculated at the neighborhood level within the 0.5-, 1.0-, and 1.5-km street network buffer from each community centroid, respectively. We finally define the neighborhood area as the 1.0-km street network buffer because it conforms to the guideline of 15-min community life cycle proposed by the Shanghai City Master Plan (2017–2035). Besides, the results from other buffer areas show little difference in the health effect of neighborhood built environment. In addition, we also include the Euclidean distance to the city center (i.e., the People Square of Shanghai) for each community to control for the locational effect of widespread surveyed communities across suburban districts.

Subjective evaluations on environmental pollution consist of

Table 3
Measurement of neighborhood environment.

Category	Variable	Description
Built environment	Population density	Average number of populations in the 100 m × 100 m grid within the 1 km street network buffer
	Street connectivity	Number of road intersections within the 1 km street network buffer
	Density of indoor gyms	Number of indoor gyms within the 1 km street network buffer
	Park accessibility	Whether there is a park within the 1 km street network buffer (1 = yes)
	The greening rate of the community	Ratio of the total area of green coverage to the total area of the community
Social environment	Neighborhood safety	Do you feel safe living in your neighborhood? (1 very unsafe to 5 very safe)
	Neighborhood attachment	Do you feel attached to your neighborhood? (1 the least to 5 the most)
Environmental pollution	Air pollution	How do you evaluate the air pollution around the community? (1 very low to 5 very high)
	Noise pollution	How do you evaluate the noise pollution around the community? (1 very low to 5 very high)

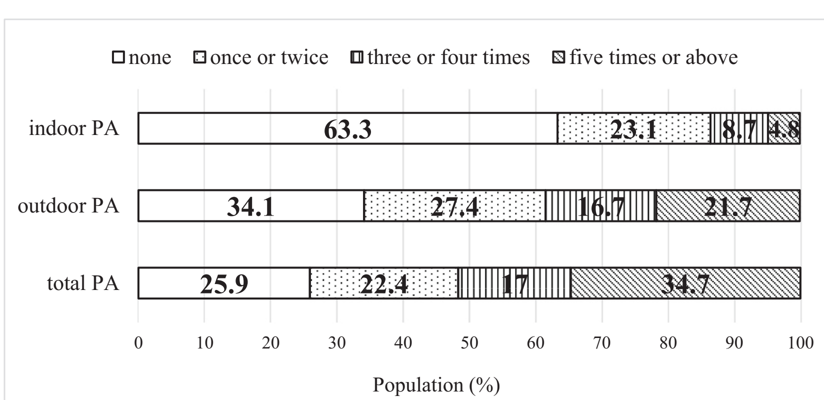

Fig. 2. Populations (%) in the frequency of indoor, outdoor and total physical activity (PA) per week.

perceived exposure to noise and air pollution in the neighborhood. Social environment is measured by self-reported levels of neighborhood safety and attachment. Fig. 3 shows the proportion of these subjective environmental variables rated by a five-point Likert scale. The mean levels of perceived neighborhood safety, neighborhood attachment, air pollution, and noise are 3.59, 3.54, 2.90, and 3.16, respectively. In particular, >70 % of the participants report their neighborhood air pollution levels as fair, high, or very high.

3.4. Measuring the outcome variables of health

Self-rated physical and mental health are the outcome variables, measured by asking the questions: In general, how would you evaluate your overall physical and mental health status, respectively? The responses are rated on a five-point Likert scale ranging from 1 (very poor) to 5 (very good). This self-reported measure can be treated as an acceptable population health indicator because of its strong association with multi-item measures of health status, as well as clinical physical and mental illnesses (Ahmad et al., 2014; DeSalvo et al., 2006). Fig. 3 illustrates the proportion of self-rated health in each level. The majority of the participants rate their physical and mental health as good or very good, with the mean value for physical health as 3.94 and for mental health as 4.04, respectively.

Considering the well-established health effect of green space, Fig. 4 demonstrates the proportion of participants reporting (very) good physical and mental health across the 38 surveyed communities with the ascending order of the greening rate of the community. Generally, there is a growth in the proportion of participants reporting good or very good health status as the greening rate of the community increases, and this rising trend is more obvious for physical health than mental health.

3.5. Statistical methods

According to the socio-ecological model, health is influenced by the factors performing at multiple levels, including individual and neighborhood levels (McLeroy et al., 1988; Sallis et al., 2006; Stokols, 1996). The cluster sampling procedure used in our study also assumes that residents from the same residential community are exposed to similar neighborhood environment and may show similar behavioral preferences. Based on these two considerations, we apply the multilevel modeling analysis to simultaneously control for the within- and between-community effects on self-rated health, and set the random intercept for each surveyed community to measure the variances in health among different communities. Before fitting the multilevel models, the simple correlation coefficients and VIF values between independent variables are tested with the results all below 0.65 and 6.0, respectively, indicating no serious multi-collinearity problems. To facilitate model interpretation and comparability of regression coefficients, the continuous independent variables are *Z*-score standardized with the mean zero. The modeling environment is Stata 15.0.

Six multilevel ordinal logistic models with the increasing complexity of variables are constructed to investigate the determinants of self-rated physical health (PH) and mental health (MH), respectively. The baseline model (Model 1 for PH and Model 7 for MH) only includes the variables of participants' socioeconomic characteristics to explain the personal determinants of long-term health status. Then, objective measures of neighborhood built environment attributes are added in Model 2 for PH and Model 8 for MH to explore the independent health effect of built environment after controlling for individual socioeconomic characteristics and the community location. In Model 3 for PH and Model 9 for MH, a series of subjective evaluations on neighborhood environmental pollution and social environment are incorporated to examine whether and how they confound the results of neighborhood built environment. Further, we take into account the variables of physical activity in Model 4 for PH and Model 10 for MH to analyze the direct and independent health effects of recreational exercises after controlling for transport-related physical activity. Finally, the interaction terms between outdoor physical activity and some neighborhood environmental attributes are constructed to investigate how physical activity moderates the associations of environmental benefits and risks with health outcomes. Specifically, two two-way interaction terms (i.e., outdoor physical activity × the greening rate of the community, outdoor physical activity × perceived air pollution exposure) are built in Model 5 for PH and Model 11 for MH. A three-way interaction term (outdoor physical activity × the greening rate of the community × perceived air pollution exposure) is included in Model 6 for PH and Model 12 for MH.

4. Model results

4.1. Physical health

Table 4 presents the multilevel model results for self-rated physical health. Model 1 shows that females, local residents, young- and older-aged (30–39 and 50–60 years old) and low-income people (monthly income <5000 RMB) tend to report better physical health. Regarding the built environment characteristics (Model 2), green coverage of the community is positively correlated with residents' physical health. A standard deviation increase in the greening rate of the community

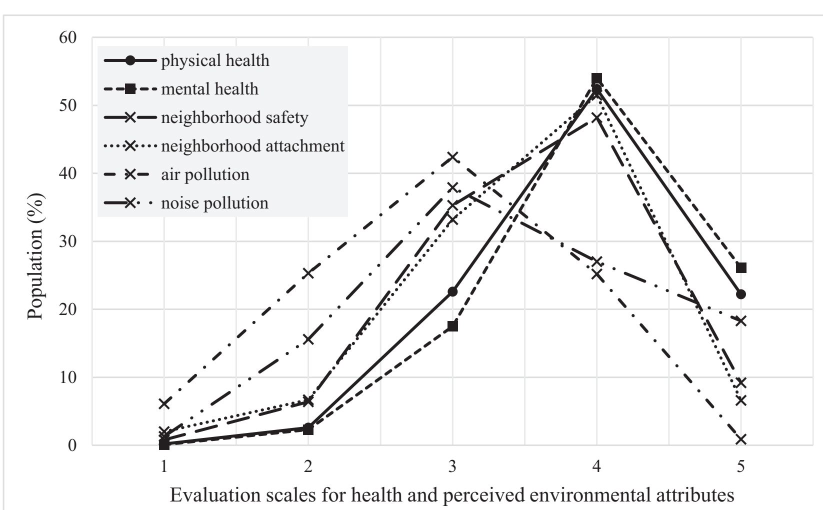

Fig. 3. Populations (%) in the scales of self-rated health levels and environmental attributes.

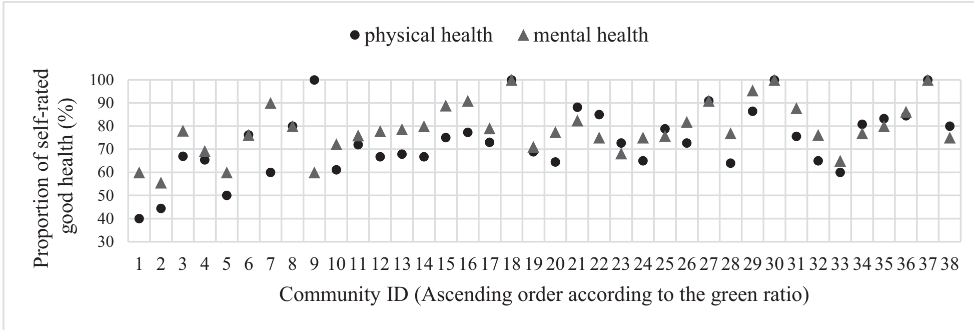

Fig. 4. Population (%) reporting good or very good health by the greening rate of the community.

would increase the odds of reporting better physical health by 14 %. Similar health benefits are found for the neighborhood with better street connectivity. However, although accessibility to indoor gyms and urban parks are positively related to physical health, their effects are not statistically significant. Besides, distance to the city center is negligibly associated with self-rated physical health, indicating that suburban residents' physical health is more related to the specific neighborhood environment than the broad geographic locations of their residential neighborhoods.

After taking into account environmental pollution and social environment, the health effects of most built environment attributes remain (Model 3). An exception is that higher population density turns to be predictive of better physical health. Furthermore, perceptions of neighborhood safety and air pollution exposure are significant indicators of physical health. Residents who perceive higher levels of neighborhood air pollution would significantly lower the odds of reporting better health by 21 %. In contrast, residents who perceive higher levels of neighborhood safety are more likely to report better physical health.

After adding the physical activity variables, indoor physical activity shows insignificant health benefits, while outdoor physical activity is significantly correlated with self-rated physical health (Model 4). Residents who engage in frequent moderate-to-vigorous outdoor exercises would increase the odds of reporting better physical health by 17 %. Besides, car commuters have a higher likelihood of reporting worse physical health than active commuters. Longer job-housing distance is surprisingly related to better physical health. This result should be treated with caution as we cannot exclude the bias from reverse causality, that is, people who are in good physical health are more likely to accept long job-housing distance instead of vice versa. Moreover, outdoor physical activity significantly moderates the relationship between green coverage of the community and physical health (Model 5). A standard deviation of the greening rate of the community is associated with a marginal health benefit by 14 % when residents take frequent outdoor exercises. However, perceived air pollution neither moderates the outdoor exercises - physical health relationship (Model 5), nor reduces the health benefits of exercises in the community of higher green coverage (Model 6).

4.2. Mental health

Table 5 presents the multilevel model results for self-rated mental health. Model 7 shows that middle-aged (30–49 years old) residents are more likely to report worse mental health than their younger counterparts (18–29 years old), whereas most of the other socioeconomic characteristics are not significantly associated with mental health. Regarding the objective built environment (Mode 8), only the greening rate of the community exhibits significant correlations with mental health. Residents living in neighborhoods with higher green coverage tend to increase the odds of reporting better mental health by 22 %.

In contrast with insignificant results of most built environment attributes, subjective measures on neighborhood environmental pollution and social environment are significantly associated with self-rated mental health (Model 9). Similar to the results for physical health, the relationship between population density and mental health turns to be marginally significant after controlling for subjective environmental determinants. However, different from Model 3, residents who are attached to their neighborhood would significantly increase the odds of reporting better mental health.

Model 10 incorporates a set of variables on recreational and transport-related physical activity. The results show that residents who keep frequent outdoor exercises for leisure would increase the odds of reporting better mental health by 23 %, while the mental health effect of indoor physical activity is insignificant, similar to the results for physical health. In addition, there is a significant and positive effect of travel satisfaction on mental health, while longer job-housing distance is modestly related to worse mental health. Regarding the interaction terms between outdoor physical activity and neighborhood environment in Model 11, the moderation of outdoor exercises is weak and insignificant for the effect of both the greening rate of the community and perceived air pollution on mental health. In Model 12, there is also no significant moderating effect of outdoor exercises on the association of combined exposure to green space and air pollution with mental health.

5. Discussion and conclusions

5.1. Discussion of main findings

Following the urban expansion in the developed world over the past few decades, rapid suburbanization in Chinese megacities has induced multiple urban, environmental and social problems, which subject suburban residents to significant health risks. Our study chooses suburban Shanghai as the case to investigate the combined effects of neighborhood environment and physical activity on residents' self-rated physical and mental health, respectively. In the following discussion, we interpret main research findings within the broad socio-spatial structure, i.e., suburbanization of Chinese megacities, according to the social-ecological model. Moreover, we compare the findings with those in developed countries with the aims of enriching the international knowledge on the mechanisms of neighborhood effects on health.

Consistent with the results in developed countries (Arcaya et al., 2016; Carlson et al., 2012; Christian et al., 2011; Moore et al., 2018), our study indicates that neighborhood built environment has modest effects on health outcomes, particularly on self-rated mental health, after taking into account individual socioeconomic compositions. An exception is that green coverage in the community is associated with self-rated physical and mental health. This is different from the evidence showing the health benefits of large-scale urban parks in cities of developed countries, where middle- and high-income residents relocate to suburbs for a green and healthy living environment (Schipperijn et al.,

Table 4
Multilevel ordinal logistic modeling results for physical health.

	Model 1		Model 2		Model 3		Model 4		Model 5		Model 6	
	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI
Cut 1	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)
Cut 2	0.02	(0.01, 0.04)	0.02	(0.00, 0.04)	0.02	(0.01, 0.04)	0.02	(0.01, 0.04)	0.02	(0.01, 0.04)	0.02	(0.01, 0.04)
Cut 3	0.30	(0.20, 0.45)	0.30	(0.20, 0.45)	0.31	(0.20, 0.46)	0.28	(0.18, 0.42)	0.29	(0.19, 0.44)	0.30	(0.20, 0.45)
Cut 4	3.45	(2.31, 5.15)	3.40	(2.26, 5.06)	3.61	(2.41, 5.40)	3.57	(2.35, 5.34)	3.52	(2.33, 5.31)	3.53	(2.34, 5.32)
Male	**1.24**	**(1.02, 1.46)**	**1.23**	**(0.99, 1.54)**	1.21	(0.95, 1.56)	1.22	(0.94, 1.57)	1.23	(0.95, 1.58)	1.22	(0.94, 1.58)
Age: 30–39	**0.72**	**(0.51, 1.00)**	**0.70**	**(0.50, 0.99)**	**0.70**	**(0.50, 0.98)**	0.73	(0.53, 1.04)	0.74	(0.54, 1.05)	0.74	(0.55, 1.05)
Age: 40–49	0.78	(0.54, 1.12)	0.75	(0.52, 1.07)	0.77	(0.54, 1.11)	0.74	(0.51, 1.07)	0.71	(0.49, 1.03)	0.71	(0.49, 1.03)
Age: 50–60	**0.54**	**(0.36, 0.80)**	**0.52**	**(0.35, 0.77)**	**0.48**	**(0.33, 0.72)**	**0.45**	**(0.30, 0.67)**	**0.47**	**(0.32, 0.69)**	**0.47**	**(0.32, 0.70)**
Local residents	0.85	(0.66, 1.10)	0.85	(0.66, 1.11)	0.85	(0.66, 1.10)	0.85	(0.66, 1.10)	0.85	(0.66, 1.10)	0.85	(0.66, 1.10)
Full-time employment	1.32	(0.95, 1.82)	1.32	(0.96, 1.82)	**1.36**	**(1.00, 1.87)**	**1.36**	**(1.00, 1.88)**	1.35	(0.97, 1.84)	1.33	(0.95, 1.83)
Household monthly income: 5000 and below	**0.64**	**(0.44, 0.93)**	**0.63**	**(0.42, 0.92)**	**0.62**	**(0.42, 0.91)**	**0.68**	**(0.47, 0.94)**	**0.67**	**(0.46, 0.93)**	**0.67**	**(0.47, 0.93)**
Housing satisfaction	**0.86**	**(0.76, 0.98)**	**0.84**	**(0.74, 0.95)**	**0.84**	**(0.74, 0.95)**	**0.88**	**(0.78, 0.97)**	**0.88**	**(0.77, 0.97)**	**0.88**	**(0.78, 0.97)**
Population density			1.08	(0.92, 1.26)	**1.18**	**(1.00, 1.39)**	**1.18**	**(1.01, 1.39)**	**1.18**	**(1.01, 1.40)**	**1.18**	**(1.01, 1.40)**
Street connectivity			**1.14**	**(1.00, 1.29)**	**1.18**	**(1.02, 1.31)**	**1.17**	**(1.00, 1.30)**	**1.17**	**(1.00, 1.30)**	**1.17**	**(1.00, 1.30)**
Density of indoor gyms			0.99	(0.85, 1.19)	0.97	(0.83, 1.15)	0.93	(0.79, 1.11)	0.95	(0.80, 1.13)	0.97	(0.82, 1.16)
Park accessibility			1.13	(0.77, 1.65)	1.20	(0.82, 1.76)	1.25	(0.85, 1.83)	1.25	(0.85, 1.83)	1.24	(0.85, 1.83)
Greening rate of communities			**1.14**	**(1.02, 1.30)**	**1.15**	**(1.02, 1.32)**	**1.16**	**(1.02, 1.33)**	**1.11**	**(1.00, 1.23)**	**1.11**	**(1.01, 1.23)**
Distance to the city center			1.02	(0.88, 1.18)	1.02	(0.88, 1.18)	1.02	(0.87, 1.18)	1.02	(0.87, 1.18)	1.02	(0.88, 1.18)
Perceived air pollution					**0.79**	**(0.62, 0.94)**	**0.79**	**(0.61, 0.94)**	**0.81**	**(0.64, 0.96)**	**0.83**	**(0.66, 0.96)**
Perceived noise pollution					0.97	(0.85, 1.10)	0.98	(0.86, 1.12)	0.96	(0.84, 1.09)	0.95	(0.84, 1.07)
Neighborhood safety					**1.18**	**(1.03, 1.35)**	**1.18**	**(1.03, 1.35)**	**1.19**	**(1.05, 1.38)**	**1.19**	**(1.06, 1.38)**
Neighborhood attachment					1.11	(0.98, 1.27)	1.11	(0.98, 1.27)	1.13	(0.99, 1.28)	1.13	(0.99, 1.28)
Indoor physical activity							0.98	(0.92, 1.05)	1.02	(0.95, 1.09)	1.02	(0.95, 1.09)
Outdoor physical activity							**1.17**	**(1.04, 1.33)**	**1.15**	**(1.03, 1.33)**	**1.15**	**(1.03, 1.33)**
Job-housing distance							**1.16**	**(1.02, 1.32)**	**1.15**	**(1.02, 1.30)**	**1.15**	**(1.02, 1.31)**
Public transport commuting							1.03	(0.75, 1.42)	1.05	(0.76, 1.48)	1.05	(0.76, 1.48)
Car commuting							**0.47**	**(0.32, 0.69)**	**0.45**	**(0.31, 0.67)**	**0.45**	**(0.30, 0.67)**
Travel satisfaction							1.11	(0.97, 1.25)	1.09	(0.95, 1.24)	1.08	(0.94, 1.23)
Outdoor physical activity × greening rate of communities									**1.14**	**(1.02, 1.25)**	**1.14**	**(1.02, 1.26)**
Outdoor physical activity × perceived air pollution									0.95	(0.83, 1.09)	0.93	(0.79, 1.06)
Outdoor physical activity × greening rate of communities × perceived air pollution											0.95	(0.72, 1.24)
Random part												
Level 2 variance (S.E.)	0.26	(0.14)	0.25	(0.12)	0.18	(0.09)	0.15	(0.07)	0.16	(0.08)	0.16	(0.08)
Likelihood-ratio test (chi2)	**7.83**		**7.37**		**5.87**		**5.60**		**5.58**		**5.57**	

Note: OR represents odds ratio and 95 % CI refers to 95% confidence intervals. Significant results at $p < 0.05$ are shown in bold.

2017; Wolch et al., 2014). Similar to our findings, a recent study in Shanghai suggests that in low-density suburban areas, neighborhood green space partially substitutes urban parks in promoting public health (Xiao et al., 2016). The rationale may be related to the specific socio-spatial pattern of suburbanization in Chinese megacities, where rapidly increasing suburban populations do not match with sufficient and accessible health-promoting environmental amenities (e.g., parks and woodlands). As a result, neighborhood-scale green space, rather than urban parks, is a preferable site for them to socialize with neighbors, participate in leisure activities, and maintain good health. Another

Table 5
Multilevel ordinal logistic modeling results for mental health.

	Model 7		Model 8		Model 9		Model 10		Model 11		Model 12	
	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI
Cut 1	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)	0.00	(0.00, 0.01)	0.00	(0.00,0.01)	0.00	(0.00,0.01)	0.00	(0.00,0.01)
Cut 2	0.02	(0.01, 0.04)	0.02	(0.01, 0.04)	0.02	(0.01, 0.04)	0.02	(0.01,0.04)	0.02	(0.01,0.05)	0.03	(0.02,0.06)
Cut 3	0.23	(0.15, 0.34)	0.22	(0.15, 0.34)	0.23	(0.15, 0.35)	0.22	(0.14,0.34)	0.22	(0.14,0.34)	0.22	(0.14,0.34)
Cut 4	2.79	(1.86, 4.18)	2.80	(1.84, 4.27)	3.08	(1.98, 4.80)	3.06	(1.97,4.77)	3.05	(1.97,4.76)	3.05	(1.96,4.76)
Male	1.07	(0.83, 1.37)	1.06	(0.82, 1.36)	1.05	(0.81, 1.35)	1.07	(0.83,1.39)	1.08	(0.83,1.40)	1.08	(0.83,1.40)
Age: 30–39	**0.70**	**(0.50, 0.99)**	**0.71**	**(0.52, 0.99)**	**0.70**	**(0.49, 0.99)**	**0.71**	**(0.50,1.00)**	0.71	(0.52,1.01)	0.72	(0.51,1.01)
Age: 40–49	**0.60**	**(0.42, 0.87)**	**0.59**	**(0.41, 0.85)**	**0.62**	**(0.43, 0.90)**	**0.59**	**(0.40,0.86)**	**0.60**	**(0.42,0.87)**	**0.60**	**(0.42,0.87)**
Age: 50–60	0.71	(0.47, 1.06)	0.69	(0.46, 1.03)	**0.63**	**(0.42, 0.95)**	**0.57**	**(0.38,0.86)**	**0.59**	**(0.40,0.89)**	**0.59**	**(0.40,0.90)**
Local residents	1.04	(0.80, 1.34)	1.04	(0.80, 1.35)	1.04	(0.80, 1.35)	1.04	(0.80,1.35)	1.04	(0.81,1.35)	1.04	(0.81,1.35)
Full-time employment	1.31	(0.95, 1.81)	1.31	(0.95, 1.81)	1.36	(0.98, 1.89)	1.32	(0.96,1.82)	1.33	(0.96,1.83)	1.32	(0.96,1.83)
Household monthly income: 5000 and below	0.93	(0.65, 1.32)	0.93	(0.65, 1.32)	0.95	(0.67, 1.36)	0.98	(0.69,1.42)	0.98	(0.68,1.42)	0.97	(0.67,1.40)
Housing satisfaction	0.90	(0.80, 1.02)	0.89	(0.79, 1.01)	**0.88**	**(0.78, 1.00)**	**0.88**	**(0.78,1.00)**	**0.89**	**(0.79,1.00)**	**0.90**	**(0.80,1.00)**
Population density			1.10	(0.94, 1.30)	**1.25**	**(1.03, 1.52)**	**1.26**	**(1.04,1.53)**	**1.27**	**(1.05,1.53)**	**1.27**	**(1.05,1.53)**
Street connectivity			1.08	(0.88, 1.24)	1.13	(0.92, 1.30)	1.12	(0.91,1.29)	1.12	(0.91,1.28)	1.11	(0.90,1.28)
Density of indoor gyms			0.90	(0.76, 1.11)	0.89	(0.74, 1.10)	0.85	(0.68,1.06)	0.86	(0.69,1.07)	0.87	(0.70,1.07)
Park accessibility			1.10	(0.72, 1.69)	1.16	(0.71, 1.90)	1.19	(0.73,1.95)	1.20	(0.75,1.96)	1.20	(0.75,1.96)
Greening rate of communities			**1.22**	**(1.04, 1.45)**	**1.23**	**(1.05, 1.47)**	**1.24**	**(1.07,1.48)**	**1.20**	**(1.04,1.45)**	**1.19**	**(1.03,1.45)**
Distance to the city center			0.99	(0.86, 1.16)	0.99	(0.85, 1.16)	1.00	(0.86,1.17)	1.00	(0.86,1.17)	1.00	(0.85,1.17)
Perceived air pollution					**0.83**	**(0.66, 0.98)**	**0.82**	**(0.65,0.98)**	**0.84**	**(0.67,1.00)**	0.85	(0.68,1.01)
Perceived noise pollution					0.91	(0.79, 1.04)	0.92	(0.80,1.07)	0.92	(0.80,1.07)	0.92	(0.80,1.07)
Neighborhood safety					**1.37**	**(1.19, 1.58)**	**1.35**	**(1.16,1.55)**	**1.35**	**(1.17,1.55)**	**1.36**	**(1.19,1.57)**
Neighborhood attachment					**1.11**	**(1.02, 1.21)**	**1.11**	**(1.02,1.20)**	**1.12**	**(1.03,1.21)**	**1.12**	**(1.02,1.22)**
Indoor physical activity							1.04	(0.91,1.17)	1.03	(0.90,1.17)	1.03	(0.90,1.16)
Outdoor physical activity							**1.23**	**(1.07,1.40)**	**1.21**	**(1.06,1.38)**	**1.21**	**(1.06,1.39)**
Job-housing distance							0.90	(0.79,1.04)	0.89	(0.78,1.02)	0.89	(0.78,1.03)
Public transport commuting							1.26	(0.90,1.76)	1.26	(0.90,1.76)	1.27	(0.90,1.78)
Car commuting							0.71	(0.48,1.04)	0.71	(0.48,1.04)	0.72	(0.48,1.06)
Travel satisfaction							**1.38**	**(1.21,1.57)**	**1.37**	**(1.20,1.57)**	**1.37**	**(1.21,1.57)**
Outdoor physical activity × greening rate of communities									1.07	(0.95,1.20)	1.09	(0.98,1.23)
Outdoor physical activity × perceived air pollution									0.89	(0.75,1.04)	0.89	(0.76,1.04)
Outdoor physical activity × greening rate of communities × perceived air pollution											0.97	(0.86,1.10)
Random part												
Level 2 variance (S.E.)	0.23	(0.11)	0.22	(0.10)	0.18	(0.08)	0.17	(0.07)	0.17	(0.07)	0.17	(0.07)
Likelihood-ratio test (chi2)	**6.43**		**6.31**		**5.64**		**5.56**		**5.58**		**5.56**	

Note: OR represents odds ratio and 95 % CI refers to 95% confidence intervals. Significant results at $p < 0.05$ are shown in bold.

possible reason is that suburban workers are exposed to multiple daily stressors, such as long commuting distance and great spatiotemporal constraints. It is the green space in the neighborhood that helps them recover from fatigue and relieve physiological stress.

Air pollution acts as an environmental stressor that does harm to people's health. Our results show that perceived exposure to air pollution in the neighborhood is a significant indicator of self-rated physical and mental health for suburban residents. Since the 1990s, land-use reform in China has accelerated the suburbanization of manufacturing industries along with serious environmental problems. Given that most of these factories are lack of clean energy sources and pollution control technology, air pollution issue cannot be substantially alleviated in the short term. Meanwhile, sprawling urban expansion increases the job-housing mismatch and people's dependence on automobile travel, which results in more traffic volumes and exhaust emissions (Tao et al., 2021). In 2017 Shanghai, for example, there were about 50 days with the air quality index larger than 100, and 170 days with $PM_{2.5}$ concentrations larger than 35 $\mu g/m^3$ (WHO interim target value). It is estimated that long-term exposures to such high levels of air pollution will lead to significantly higher all-cause mortality for susceptible populations (World Health Organization, 2005).

As the social construct of neighborhood environment, our study finds that perceived neighborhood safety and attachment are associated with residents' self-rated health outcomes, especially with mental health. When residents feel unattached and insecure in their living space, they might be reluctant to participate in outdoor activities. This is particularly the case for socioeconomically disadvantaged neighborhoods where a sense of unsafety undermines the resilience from stress, depressive symptoms, and other negative emotions (Tao et al., 2019). In contrast, close social contact and strong neighborhood attachment make for developing a healthy mindset through the support of a stable social network and the dissemination of health-enhancing information (Craveiro, 2017; Liu et al., 2021). In addition, our study finds that the health effect of population density turns to be significant after controlling for social environment. It is possible that high population density in the suburban neighborhood acts as a catalyst of close and friendly relations with neighbors, thereby yielding health gains.

The health benefits of recreational physical activity are contingent on specific contexts where the exercises take place. Specifically, frequent outdoor exercises are strongly correlated with better self-rated health, both in physical and mental dimensions. This accords with the western evidence that a physically active lifestyle in the outdoor context not only reduces the risks of heart attack, obesity and, some NCDs, but also improves health-related quality of life and psychological status (Koohsari et al., 2013; Puett et al., 2014; Ambrey, 2016). However, we do not observe similar health benefits of exercises indoors as outdoors. Besides, our results show that the density of indoor gyms around the neighborhood is not independently related to self-rated health outcomes, possibly because the high costs and limited capacity of these indoor gyms impede their large-scale utilization and thus fail to improve public health.

Moreover, the results of moderating analysis show that outdoor physical activity is a significant pathway for explaining the relationship between the greening rate of the community and self-rated physical health. It is the neighborhood-scale green space, rather than urban parks away from residences, that provides an accessible, friendly and attractive environment for suburban residents to participate in recreational exercises with gains in physical health. However, outdoor physical activity is not a significant moderator between air pollution exposure and health outcomes, and perceived air pollution does not significantly reduce the health benefit of outdoor exercises in the neighborhood green space. This finding is supported by another cross-national research showing that in the scenario of highly polluted environment, residents are more aware of the health risks of air pollution and would adjust their behaviors to avoid outdoor activities on polluted days (Giallouros et al., 2020).

5.2. Implications for neighborhood health research and practices

Our study contributes to the international knowledge on the determinants of health from the perspective of neighborhood effects. Except for individual socioeconomic compositions, places structurally influence individual health-related behaviors and health outcomes through the contextual exposure to neighborhood environment. Simply put, if residing in an underdeveloped neighborhood environment poses an independent threat to residents' health, the efficacy of individual-level behavior and health interventions would be moderated for underestimating the structural role of residential neighborhoods. Moreover, this contextual perspective on health determinants has its advantages in not only integrating the physical and social constructs of the neighborhood environment, but also differentiating the geographic context of health-related behaviors (e.g., indoors or outdoors, and outdoor activities with varying levels of exposure to nature and environmental pollution) for explaining the place-health nexus.

Our study has some policy implications for building health-supportive neighborhoods in Chinese cities and beyond. Generally, our research findings lend empirical support to the widespread international practice that employs place-based interventions in promoting population health (e.g., Giles-Corti et al., 2013; Sampson, 2012; Wheaton et al., 2015). Therefore, public health policies are encouraged to shift the sole focus on changes in individual health-related lifestyles by taking account of structural and contextual factors, such as neighborhood effects on health. Based on the case of suburban Shanghai, our study has some specific suggestions for health-oriented neighborhood and urban planning in cities of China and other developing countries where rapid suburbanization is or about to be underway. First, the construction and renovation of easy-access, small-scale and evenly distributed green space in suburban neighborhoods is promising in encouraging more recreational exercises and improving residents' health status. Second, developing job sub-centers and public transportation hubs in the suburb will have great potential to achieve the job-housing balance, reduce pollutant emissions, and produce health benefits. Third, new town construction characterized as high density and compact patterns in Chinese megacities should be linked to the target of developing a more livable and friendly social environment beneficial to public health and well-being.

5.3. Research limitations and future research agenda

We acknowledge some limitations of our study and have some suggestions for future research. First, we used a mixture of objective and subjective measures on neighborhood environment due to the data constraints. Especially, the perceived measure on environmental pollution suffers the recall bias and exposure misclassification, which may explain the reason for the insignificant health effect of exercising in an air polluted environment. Future research would benefit from collecting objective information on residents' real-time environmental exposure, and estimating their direct effects, as well as indirect effects through perceived exposure, on health outcomes. Geographical Ecological Momentary Assessment, which integrates the real-time measure on geographical locations, environmental exposures, and affective and cognitive reactions, is a viable way to examine the exposure-effect relationship and identify the effect threshold of environmental attributes (Kou et al., 2020; Tao et al., 2020).

Second, our delineation of the neighborhood unit still has its problem although we refine the commonly-used census-based measure to follow the guideline of 15-min community life cycle in Shanghai and conduct several sensitivity analyses to fit the neighborhood boundary based on different distance thresholds. In this regard, not only multifaceted environmental attributes possibly exert health effects at different spatial scales (Petrović et al., 2020), but also people's activity-travel behaviors are not restricted in the residential neighborhoods and thus their environmental exposures are dynamic over space and time (Kwan, 2018). Therefore, we advocate for future research to place the individual person at the center of neighborhood health research and “consider alternative ways to measure the wider sociospatial context of people” (Petrović et al., 2020), such as operationalizing people's contextual exposures at both residential neighborhoods and activity space, and identifying the multiscalar neighborhood effects on health.

Third, our study follows a cross-section design, which limits the ability to understand the nuanced mechanism underlying neighborhood effects on health and fails to uncover the place-health causality. Specifically, similar socioeconomic groups are likely to be sorted into certain neighborhoods according to their disposable socioeconomic resources, behavioral orientations (e.g., a physically active lifestyle) and residential preferences (e.g., greening rate of the neighborhood). This selection process may overestimate the effect of neighborhood environment on individual health. Another related issue is that neighborhood-level socioeconomic compositions may exert an additional impact on health beyond the individual socioeconomics (e.g., through collective social norms and actions; Pearce et al., 2012). To clarify the dynamic process and causality of neighborhood effects on health, future studies are recommended to employ qualitative analysis, longitudinal designs that follow residents over time, and nature experiments such as comparing residents' health outcomes before and after residential relocation. Besides, we recommend further examining the extent to which population health and health inequalities are a product of the interactions between individual-level and neighborhood-level socioeconomic compositions, and how these interactions unfold over time.

5.4. Concluding remarks

Drawing upon an activity and health survey in suburban Shanghai in 2017, our study draws upon a series of multilevel models to investigate the role of a wide range of both objective and subjective measures on neighborhood environment and physical activity in suburban residents' self-rated physical and mental health, respectively. Our results show that contextual neighborhood environment matters in its own right as the determinants of health after individual socioeconomic compositions are accounted for. Three main findings are that: 1) Green space in the neighborhood, rather than accessibility to large-scale urban parks, is an important indicator of suburban residents' self-rated physical and mental health; 2) Subjective evaluations on neighborhood safety and air pollution are significantly associated with both physical and mental health, while strong neighborhood attachment is a significant indicator of better mental health; 3) Outdoor physical activity for leisure, particularly in the neighborhoods with more green space, is conducive to better physical and mental health, while indoor physical activity is not independently related to self-rated health outcomes.

Neighborhood effects on health is a complex and promising research topic involving a myriad of ways in which neighborhoods act as a socio-spatial determinant of health. Our study is one of the first steps in this direction by including both physical and social constructs of neighborhood environment and differentiating the geographical contexts of physical activity in unpacking the place-health nexus. Future research will benefit from longitudinal research designs to better understand how contextual and compositional neighborhood environments dynamically shape and reshape residents' health-related behaviors and health outcomes at multiple spatiotemporal scales.

Author statement

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CRediT authorship contribution statement

Yinhua Tao: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Jing Ma:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Yue Shen:** Conceptualization, Supervision. **Yanwei Chai:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that there is no conflict of interest.

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