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Socioeconomic status as an effect modifier of the association between built environment and mortality in elderly Hong Kong Chinese: A latent profile analysis

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ABSTRACT

Background: Previous studies have focused on associations between individual built environment (BE) characteristics and mortality, and found the BE-mortality associations differed by socioeconomic status (SES). Different individual BE characteristics may have different impacts on health and thus could interact. Combinations of BE characteristics may be a better approach to explore the BE-mortality associations.
Objectives: This study aimed to investigate the associations of BE pattern with mortality in a prospective cohort of elderly Hong Kong Chinese (Mr. OS and Ms. OS Study), and assess whether the BE-mortality association differed by SES.
Methods: Between 2001 and 2003, 3944 participants aged 65–98 years at baseline were included in the present analysis. BE characteristics were assessed via Geographic Information System. Data on all-cause and cause-specific mortality were obtained from the Hong Kong Government Death Registry. Latent profile analysis was used to derive BE class, and the Cox proportional hazards model was used to estimate hazard ratios (HRs) and 95% confidence intervals (CIs).
Results: Three BE classes were identified. During a total of 53276 person-years of follow-up, 1632 deaths were observed. There were no significant associations of BE class with all-cause and cause-specific mortality. However, we found the associations of BE class with all-cause mortality were modified by SES. In comparison with Class 3 (characterized by greater green space), HRs (95%CIs) were 0.72 (0.54, 0.97) for Class 1 (characterized by greater commercial land use) and 0.77 (0.64, 0.94) for Class 2 (characterized by greater residential land use) among low-SES participants. The associations were stronger among high-SES participants, with 0.55 (0.33, 0.89) for Class 1 and 0.68 (0.48, 0.97) for Class 2. In contrast, Class 2 (HR 1.18, 95%CI 1.01–1.39) had a higher mortality risk compared with Class 3 among middle-SES participants.
Conclusions: Our findings provide new evidence on the role of SES as an effect modifier of BE pattern and mortality. BE pattern has a varied effect on mortality risk for different SES groups.

1. Introduction

Built environment (BE), which refers to human-made physical environment surroundings and conditions (e.g., buildings and green space) (Travert et al., 2019), is one of the key determinants of health and well-being. BE, such as green space, has been linked with decreased non-accidental, circulatory-cause, respiratory-cause, and all-cause mortality (Dalton and Jones, 2020; Hartig et al., 2020; Iyer et al.,

Abbreviations: BE, built environment; CI, confidence interval; HR, hazard ratio; IADL, Instrumental Activities of Daily Living; LPA, Latent profile analysis; MMSE, Mini-Mental State Examination; SES, socioeconomic status.

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2020; Ji et al., 2020; Rojas-Rueda et al., 2019; Sun et al., 2020). A systematic review of cohort studies reported that 7 of 9 included studies found significant inverse associations of increases in green space with all-cause mortality risk (Rojas-Rueda et al., 2019). Only one study in the above systematic review was not conducted in a high-income country (China), and interestingly, the magnitude of association in China was weaker than those reported in high-income countries (e.g., the USA and Canada) (Rojas-Rueda et al., 2019). This indicates that socioeconomic status (SES) may modify the association of green space with mortality.

Previous studies have investigated the effect modification of SES on associations between green space and mortality, but the results are mixed. Several longitudinal studies have found significant effect modification of SES, and higher protective effects of green space were seen among participants with high-SES (Crouse et al., 2017; Ji et al., 2019; Vienneau et al., 2017; Villeneuve et al., 2012). For instance, in a cohort study, consisting of 4.2 million adults from the Swiss National Cohort, hazard ratios (HRs) and 95% confidence intervals (CIs) of natural cause mortality for per interquartile range increase in green space were 0.95 (0.94, 0.96) in lowest-SES quartile, while 0.91 (0.90, 0.93) in highest-SES quartile (Vienneau et al., 2017), possibly because advantaged socioeconomic groups have better access to health care, baseline health status, and nutrition. However, several other longitudinal studies have failed to observe a significant modification of SES on green space-mortality associations (Nieuwenhuijsen et al., 2018; Wilker et al., 2014; Zijlema et al., 2019).

Most longitudinal studies have focused on the associations of green space with mortality and how the green space-mortality associations have been modified by SES, while other BE characteristics have been less well-studied, such as open space and residential density. Another major limitation of previous research regarding the associations of BE characteristics with mortality has been that they either focused on only one BE characteristic or unique index drawn from multiple BE characteristics (e.g., walkability index). The role of BE on health is complex, since different individual BE characteristics that may have different impacts on health may interact. Therefore, combinations of BE characteristics may be a better approach to capture complex patterns of BE characteristics, and examine the impact of BE on health (Frank et al., 2010). A few cross-sectional studies have studied BE patterns, by classifying individuals into discrete subgroups using data-driven statistical methods such as latent profile analysis (LPA), and investigated the associations of LPA-derived BE patterns with physical activity, and found that certain BE patterns had differences in physical activity level (e.g., BE pattern characterized by greater park access and residential density had higher physical activity level) (Adams et al., 2011, 2012, 2015; Todd et al., 2016; Wall et al., 2012).

So far, to the best of our knowledge, there has been no longitudinal study investigating the association between BE pattern and mortality risk. Therefore, the present study aimed to investigate the associations of BE pattern with mortality risk in a prospective cohort of elderly Hong Kong Chinese citizens in Hong Kong, and assess whether the BE pattern-mortality association differed by SES.

2. Materials and methods

2.1. Study design and population

The present study was based on the Mr. OS and Ms. OS Study (Hong Kong), a community-based prospective cohort study examining determinants for osteoporosis in elderly Hong Kong Chinese (Kwok et al., 2017; Lin et al., 2020). Four thousand older adults (2000 men and 2000 women, respectively), aged 65–98 years, were recruited between August 2001 and December 2003 via public advertisement at community centers in Hong Kong. A stratified sampling method was used, so approximately 33% of participants were in each of the age groups: 65–69, 70–74, and 75+. We excluded those who were unable to walk independently and refused to provide written informed consent. By September 2017, the participants were followed up for four rounds in 2003–2005, 2005–2007, 2008–2010, and 2015–2017. Among 4000 participants, 56 participants were excluded due to without a valid address. Finally, 3944 participants were included in the present analysis. The study was approved by the Clinical Research Ethics Committee of the Chinese University of Hong Kong, and all participants provided written informed consent.

2.2. Measurement of built environment

Geographic Information System-based BE data were acquired from iB1000 Topographical Dataset of the Hong Kong Lands Department. This dataset was acquired from government records of buildings and their master layout plan, and land-use zoning information. The dataset is regularly updated, and the data updated in 2018 were used in the present analysis. BE data in the format of shapefiles, including building height, building ground coverage, green space, and various land use types, were obtained and subsequently rasterized with a spatial resolution of 1 m, using ArcGIS 10.3 software (ESRI Inc, Redlands, CA, USA). A 300 m buffer around the participants' addresses was used to calculate the standardized building height, the percentage of building ground coverage, green spaces, and the percentage of industrial, residential, commercial, government, institution, and community land uses (Table 1) to represent the neighborhood environment that the participants were exposed to.

2.3. Mortality ascertainment

Data on all-cause mortality and cause-specific mortality were obtained from the Hong Kong Government Death Registry, and data updated on January 31, 2019 were used in the present analysis. Causes of death were coded based on the 10th revision of the International classification of diseases (ICD-10). Mortality attributable to all-cause, neoplasms (C00-D48), respiratory diseases (J00-J99), and circulatory diseases (I00–I99) were generated.

2.4. Data collection

Face-to-face interviews were conducted by trained investigators to collect the following information: socio-demographic characteristics (age, sex, marital status, education level, and SES), lifestyles (alcohol drinking, smoking, and physical activity), self-reported health conditions, functional impairment, cognitive function, and history of chronic diseases and medications. SES was assessed by the self-reported socioeconomic ladder, which consists of ten rungs, with the top rung representing people with the most income, education level, and respected jobs, and the bottom rung representing people at the other extreme (Hong Kong Ladder) (Adler et al., 2000). The physical activity level was assessed using the Physical Activity Scale for the Elderly questionnaire (Washburn et al., 1993). Functional impairment was measured using Instrumental Activities of Daily Living (IADL) questionnaire. Cognitive

Table 1
Built environment characteristics.

	Min	P25	P50	P75	Max
Standardized building height, m	0.00	24.3	31.8	38.4	74.8
Mean sky view factor	0.25	0.54	0.62	0.69	1.00
Building ground coverage, %	0.00	0.15	0.21	0.29	0.52
Green space, %	0.00	4.46	13.1	34.0	100.0
Open space, %	0.00	1.56	5.06	9.70	47.9
Road coverage, %	0.00	13.1	17.2	21.7	37.9
Industrial land use, %	0.00	0.00	0.00	1.03	38.3
Residential land use, %	0.00	29.1	36.9	46.1	99.5
Commercial land use, %	0.00	0.00	0.07	1.45	32.4
Government, institution and community land use, %	0.00	2.97	6.54	10.4	51.7

function was assessed using Mini-Mental State Examination (MMSE). Number of chronic diseases was calculated through self-reported presence of 12 common chronic diseases or symptoms (i.e., diabetes, hypertension, cardiovascular diseases, stroke, cancer, Parkinson's disease, chronic obstructive lung disease, glaucoma, cataracts, arthritis, and dizziness.) and was categorized into 0, 1–2 or ≥3 chronic diseases. Anthropometric measurements were also carried on. Weight and height were measured with the participants wearing light clothing but shoes-off, and BMI was calculated as weight (kg)/height (m)^2. Waist and hip circumference were measured.

2.5. Statistical analysis

2.5.1. Latent profile analysis

To identify the unique pattern of diverse BE characteristics from 10 BE characteristics (continuous variables), we used LPA to derive several discrete clusters. LPA was a useful approach for classifying individuals into discrete subgroups based on their unique response patterns (Berlin et al., 2014; Lin et al., 2020; Todd et al., 2016). To determine the optimal number of clusters, models with 1–9 classes were identified. A range of model fit statistics (e.g., Akaike information criteria, Bayesian information criteria, and entropy ≥0.9; detailed information of statistics is provided in Table S1) were used for model selection (Berlin et al., 2014).

2.5.2. Main analysis

Baseline characteristics of study participants by BE class were examined by ANOVA (continuous variables) or chi-squared test (categorical variables). The Cox proportional hazards models were used to estimate HRs and 95%CIs of Class 1 and Class 2 (compared with Class 3) for mortality outcomes. Survival time was defined from the date of baseline investigation until the date of death or the latest database update (January 31, 2019), whichever came first. Two models were constructed to control potential confounders, because previous studies suggested that these covariates might affect the associations between BE and mortality risk (Dzhambov et al., 2020; Rojas-Rueda et al., 2019). Model 1 adjusted for age and sex; model 2 adjusted for age, sex, marital status, education level, SES, alcohol drinking, smoking, number of chronic diseases, IADL score, body mass index, waist to hip ratio, physical activity, and MMSE score.

2.5.3. Stratified analysis

Stratified analysis was conducted to explore the effect modification of SES (low, 1–3; middle, 4–6; high, 7–10) on the association of BE class with all-cause mortality. Interaction of BE class with SES was examined, by including a two-way interaction term between BE class and SES in the above model 2, and results of stratified analysis were presented (adjusted for age, sex, marital status, education level, alcohol drinking, smoking, number of chronic diseases, IADL score, body mass index, waist to hip ratio, physical activity, and MMSE score). We also examined interactions of individual BE characteristics (per 1 standard deviation increase) with SES on all-cause mortality and presented results of stratified analysis.

All analyses were conducted by R version 3.6.2 (R Development Core Team, Vienna, Austria) and RStudio version 1.2.1335 (RStudio, Boston, USA), using "survival" and "forestplot" packages. A two-tailed *P*-value <0.05 was considered statistically significant.

3. Results

3.1. Latent profile analysis

Model fit statistics for LPA are presented in Table S1. Models with 4–9 classes were excluded, because these models had smaller entropy value (≤0.89), minimum of the average latent class probabilities (≤89%), and contributed small classes (≤5% of the sample). Bootstrap likelihood ratio test (*P*-value <0.001) indicated that a 3-class model was a better solution than a 2-class model, and a 3-class model also contributed reasonable sample sizes per class (≥17% of the sample). Finally, a 3-class model was chosen. Fig. 1 presents the standardized mean (Z-score) for each BE characteristic by the 3-class solution. Class 1 was characterized by greater coverage of building ground coverage, commercial land use, road coverage, and industrial land use, and represented 16.9% of participants (N = 665) and labeled "commercial area". Class 2 (labeled "residential area") was the largest class (accounted for 59.3% sample, N = 2300), characterized by high open space, residential land use and a mix of other BE characteristics. Class 3 was characterized by high coverage of green space and sky view factor and represented 24.8% of the sample (N = 979) and was labeled "area near green space". The geographical distribution of the participants' addresses at baseline is presented in Fig. S1.

3.2. Main analyses

Detailed characteristics of participants over the study period were reported in previous studies (Lin et al., 2020). Among 3944 participants, the mean age was 72.5 (5.2) years at baseline. The baseline characteristics by BE class are presented in Table 2. Participants in Class 1 were more likely to be younger, male, married, and had higher education level, SES, and MMSE score. Participants in Class 3 had a higher proportion of participants with chronic diseases (58.8% with 1–2 chronic disease, and 26.8% with 3 or more).

Among 3944 participants, with a total of 53276 person-years of follow-up (median follow-up of 15.5 years), we observed 1632 deaths (1002 men and 630 women) between August 2001 and January 2019. Multivariable adjusted HRs (95%CIs) are presented in Table 3. In both model 1 and model 2, Class 1 and Class 2 tended to have a lower all-cause mortality risk compared with Class 3, but the associations were not statistically significant. In model 2, HRs (95%CIs) were 0.91 (0.77, 1.06) for Class 1, and 0.96 (0.85, 1.08) for Class 2. Similarly, there were no significant associations between BE class and cause-specific mortality outcomes.

3.3. Stratified analyses

There was a significant interaction of BE class with SES ($P = 0.001$) on all-cause mortality. In the subsequent stratified analysis by SES (Fig. 2), Class 1 and Class 2 had a lower all-cause mortality risk compared with Class 3 among low- and high-SES participants. Among low-SES participants, HRs (95%CIs) were 0.72 (0.54, 0.97) for Class 1 and 0.77 (0.64, 0.94) for Class 2. The magnitudes of associations were stronger among high-SES participants, with 0.55 (0.33, 0.89) for Class 1 and 0.68 (0.48, 0.97) for Class 2, but the 95%CIs were overlapping. In contrast, Class 1 (HR 1.13, 95%CI 0.92–1.40) and Class 2 (HR 1.18, 95% CI 1.01–1.39) tended to have a higher mortality risk compared with Class 3 among middle-SES participants. Similarly, there were significant interactions of individual BE characteristics with SES ($P < 0.05$), including mean sky view factor, building ground coverage, green space, open space, and industrial land use (Table S2). In stratified analysis, the association directions were also different across SES (low-and high vs middle). For instance, per 1 standard deviation increase in green space corresponded to HRs of 1.10 (low-SES), 0.92 (middle-SES), and 1.18 (high-SES).

4. Discussion

In this study, we failed to observe statistically significant associations between BE class and mortality risk. However, we found the associations of BE class with all-cause mortality were modified by SES. In comparison with Class 3 (characterized by greater green space and sky view factor), Class 1 (characterized by high proportion of commercial land use) and Class 2 (characterized by greater open space and proportion of residential land use) had a lower all-cause mortality risk among low- and

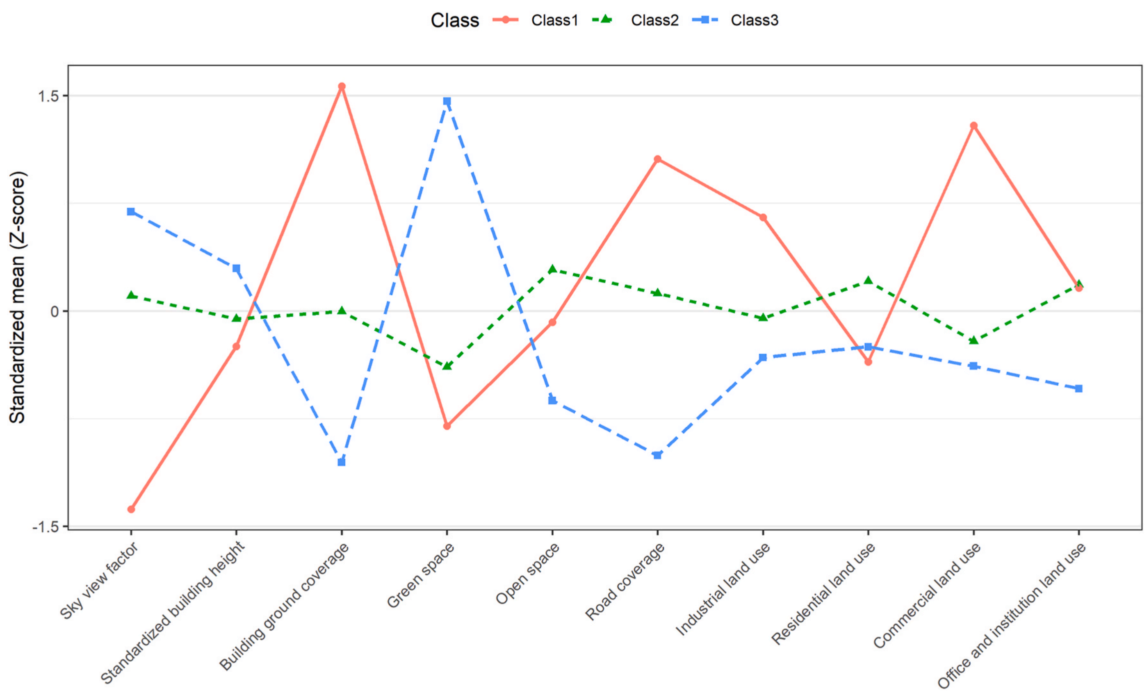

Fig. 1. Standardized mean (Z-score) for each built environment characteristics by latent class.

Table 2
Baseline characteristics of participants by built environment class (Lin et al., 2020).

	Class 1 (N = 665)	Class 2 (N = 2300)	Class 3 (N = 979)	*P*-value[a]
	Mean (standard deviation) or number (%)			
Age, years	71.9 (4.8)	72.6 (5.3)	72.7 (5.3)	0.004
Sex, female, N (%)	273 (41.1)	1182 (51.4)	517 (52.8)	<0.001
Marital status, N (%)				<0.001
Married	525 (78.9)	1596 (69.4)	674 (68.8)	
Widowed	117 (17.6)	603 (26.2)	251 (25.6)	
Separated or divorced	10 (1.5)	51 (2.2)	27 (2.8)	
Single (never married)	13 (2.0)	50 (2.2)	27 (2.8)	
Education level, N (%)				<0.001
No education	90 (13.5)	525 (22.8)	228 (23.3)	
Primary school or below	308 (46.3)	1137 (49.4)	532 (54.3)	
Secondary school or above	267 (40.2)	638 (27.8)	219 (22.4)	
Socioeconomic status, N (%)				0.005
Low (1–3)	162 (24.4)	708 (30.8)	318 (32.5)	
Middle (4–6)	419 (63.0)	1292 (56.2)	542 (55.4)	
High (7–10)	84 (12.6)	300 (13.0)	119 (12.2)	
Alcohol drinking, N (%)	102 (15.3)	295 (12.8)	118 (12.1)	0.137
Smoking, N (%)	43 (6.5)	157 (6.8)	73 (7.5)	0.711
Number of chronic diseases, N (%)				0.030
0	117 (17.6)	390 (17.0)	141 (14.4)	
1 or 2	376 (56.5)	1230 (53.5)	576 (58.8)	
≥3	172 (25.9)	680 (29.5)	262 (26.8)	
Number of IADL disabilities, N (%)				0.055
0	521 (78.3)	1679 (73.0)	728 (74.4)	
1 or 2	85 (12.8)	337 (14.7)	145 (14.8)	
≥2	59 (8.9)	284 (12.3)	106 (10.8)	
Body mass index, kg/m^2	23.8 (3.3)	23.7 (3.3)	23.5 (3.4)	0.067
Waist to hip ratio	0.92 (0.07)	0.92 (0.07)	0.92 (0.07)	0.668
PASE score	91.6 (41.7)	90.4 (43.0)	92.3 (43.2)	0.319
MMSE score	26.3 (3.2)	25.5 (3.8)	25.5 (3.7)	<0.001

Abbreviations: IADL, Instrumental Activities of Daily Living; MMSE, Mini-Mental State Examination; PASE, Physical Activity Scale for the Elderly.
[a] *P*-value was estimated by ANOVA (continuous variables) or chi-square test (categorical variables).

high-SES people, while tended to have a higher mortality risk among middle-SES people.

4.1. In comparison to previous studies

A few cohort studies have found effect modification of SES on associations between individual BE characteristics (e.g., green space) and mortality (Crouse et al., 2017; Ji et al., 2019; Vienneau et al., 2017; Villeneuve et al., 2012). Three cohort studies have reported increasingly prospective effects of green space in each increasing SES quartile for mortality (Crouse et al., 2017; Vienneau et al., 2017; Villeneuve et al., 2012). Another cohort study reported that the protective effects of green space were observed in high-SES people, but not low-SES people (Ji et al., 2019). Our findings also showed effect modification of SES on associations of BE class and several individual BE characteristics (including sky view factor, building ground coverage, green space, open space, and industrial land use) with mortality. We also found that magnitudes of associations were stronger among high-SES people than those observed among low-SES people (Fig. 2 & Table S2). Possible explanations are that people with high-SES might have better access to health care, healthier lifestyles, and better health status (Adler and Newman, 2002; Pampel et al., 2010). However, our findings should be interpreted with caution since the 95%CIs were overlapping. Besides, we observed that BE-mortality associations among participants with low- and high-SES and participants with middle-SES were in opposite directions. For instance, an increase in green space was associated with lower mortality risk among middle SES participants, while associated with higher mortality risk among low- and high-SES participants.

4.2. Explanations for findings among low- and high-SES people

Our findings indicates that among both low- and high-SES people, those who lived near greater coverage of building ground coverage and commercial land use (Class 1) and greater open space and proportion of residential land use (Class 2) had a lower all-cause mortality risk compared with people living near greater green space and sky view factor (Class 3). Although previous studies have found that green space is positively associated with chronic obstructive pulmonary disease (Fan

Table 3
Hazard ratios and 95% confidence intervals of all-cause and cause-specific mortality between built environment class in the Mr. OS and Ms. OS Study (N = 3944 with 1632 deaths)[a].

Outcomes	Statistical model	Built environment class		
		Class 1	Class 2	Class 3
All-cause mortality	Number of participants	665	2300	979
	Cases/person-years	254/9194	958/30908	420/13174
	Model 1[b]	0.87 (0.74, 1.02)	0.96 (0.86, 1.08)	1.00 (reference)
	Model 2[c]	0.91 (0.77, 1.06)	0.96 (0.85, 1.08)	1.00 (reference)
Neoplasms-cause mortality	Number of participants	493	1637	708
	Cases/person-years	82/7387	295/24125	149/10357
	Model 1[b]	0.74 (0.57, 0.97)	0.85 (0.70, 1.03)	1.00 (reference)
	Model 2[c]	0.77 (0.59, 1.01)	0.83 (0.68, 1.01)	1.00 (reference)
Circulatory-cause mortality	Number of participants	478	1551	647
	Cases/person-years	67/7319	209/23483	88/9966
	Model 1[b]	1.03 (0.75, 1.42)	0.99 (0.77, 1.28)	1.00 (reference)
	Model 2[c]	1.05 (0.76, 1.45)	0.99 (0.77, 1.28)	1.00 (reference)
Respiratory-cause mortality	Number of participants	469	1589	670
	Cases/person-years	58/7297	247/24299	111/10248
	Model 1[b]	0.72 (0.52, 0.99)	0.87 (0.70, 1.09)	1.00 (reference)
	Model 2[c]	0.77 (0.55, 1.06)	0.90 (0.72, 1.13)	1.00 (reference)

[a] Hazard ratios and 95% confidence intervals were estimated for Class 1 and Class 2 compared with Class 3.
[b] Model 1: adjusted for age and sex.
[c] Model 2: adjusted for age, sex, marital status, education level, socioeconomic status, alcohol drinking, smoking, number of chronic diseases, Instrumental Activities of Daily Living score, body mass index, waist to hip ratio, physical activity, and Mini-Mental State Examination score.

et al., 2020; Markevych et al., 2017), our finding is inconsistent with most of previous studies reporting a protective effect of green space on all-cause mortality (Dalton and Jones, 2020; Hartig et al., 2020; Iyer et al., 2020; Ji et al., 2020; Rojas-Rueda et al., 2019; Sun et al., 2020). There are several possible explanations for the inconsistencies. Parks are one of the most common types of green space in Chinese cities. In a subgroup of our participants (n = 1030), we investigated how often they went to parks. Fifty-four percent of participants with low-SES and 49% of participants with middle-SES reported that they went to parks every day, while only 37% of high-SES participants went to parks every day. This suggests that participants with high-SES had a lower proportion of green space access, which means they might tend to spend less time on physical activity in green space. Although participants with low-SES had a higher proportion of green space access, green space within neighborhoods of low-SES people might be of poor quality and availability (e.g., they provide few opportunities and recreational facilities to promote physical activity) (Astell-Burt et al., 2014; Hoffimann et al., 2017). However, we were unable to assess the quality and availability of green space due to the absence of data. In summary, participants in Class 3 with low- and high-SES may have lower physical activity levels, which has been linked to higher mortality risk (Nocon et al., 2008).

On the other hand, commercial areas (Class 1) and residential areas (Class 2) had a higher residential density compared with areas near green space (Class 3), while a neighborhood with a high residential density is more likely to have a more accessible destination within a walking distance around home, which promotes transport-related walking (Forsyth et al., 2016). Residential density also has been reported to be inversely associated with cardio-metabolic disease risk (Chandrabose et al., 2019; Glazier et al., 2014; Griffin et al., 2013; Paquet et al., 2014; Villanueva et al., 2013).

4.3. *Explanations for findings among middle-SES people*

In contrast, we found that among middle-SES people, those who lived near residential areas (Class 2) had a higher all-cause mortality risk compared with people living near greater green space and sky view factor (Class 3). As mentioned above, participants with middle-SES had a higher proportion of green space access than participants with high-SES. Besides, a previous study reported that green space within neighborhoods of middle-SES people had greater quality and availability than green space within neighborhoods of low-SES people, and had more attractive aesthetic features (e.g., artistic feature, historical feature, and water feature) than both low- and high-SES neighborhoods (Vaughan et al., 2013). Thus, among middle-SES people, those who lived near greater green space are more likely to engage in physical activity and have a lower mortality risk. Another potential path for linking higher green space to lower mortality risk is that green space can reduce air pollution levels (Markevych et al., 2017), since air pollution has been found to have negative impact on health and life expectancy (Qi et al., 2020; Tian et al., 2020; Yang et al., 2020).

4.4. *Strengths and limitations*

Study strengths included objective measure of BE and a large sample cohort study. Besides, to the best of our knowledge, this is the first study to examine the associations of BE pattern with mortality risk, and whether the associations were modified by SES. Several limitations should be considered. First, SES was assessed by subjective socioeconomic ladder, but not objective indicators, such as income, which may cause potential misclassification. However, previous studies highlighted that subjective socioeconomic ladder can be more consistently and strongly associated with overall health than objective socioeconomic indicators, since subjective socioeconomic ladder more accurately reflect overall SES (Adler et al., 2000; Operario et al., 2004). Second, we did not have information on the types and quality of green space participants were exposed to, nor did we have exact information on whether participants spent time in green space. But we investigated how often they went to parks in a subgroup (n = 1030), since parks are one of the most common types of green space in Chinese cities. Third, BE characteristics were only measured at baseline and BE characteristics might have changed during follow-up or participants might move to new address. Besides, the Dataset of the Hong Kong Lands Department used to calculate BE characteristics was updated in 2018. These might have weakened the true associations, but only 5.2% of participants reported moving to the new address and BE characteristics would not have substantial change within a decade (Hirsch et al., 2016). Fourth, our findings were based on elderly Hong Kong Chinese aged 65 years and older, and thus the generalization of our findings should be cautious. Finally, although we adjusted for multiple potential confounders, residual confounding due to unmeasured confounders could not be excluded.

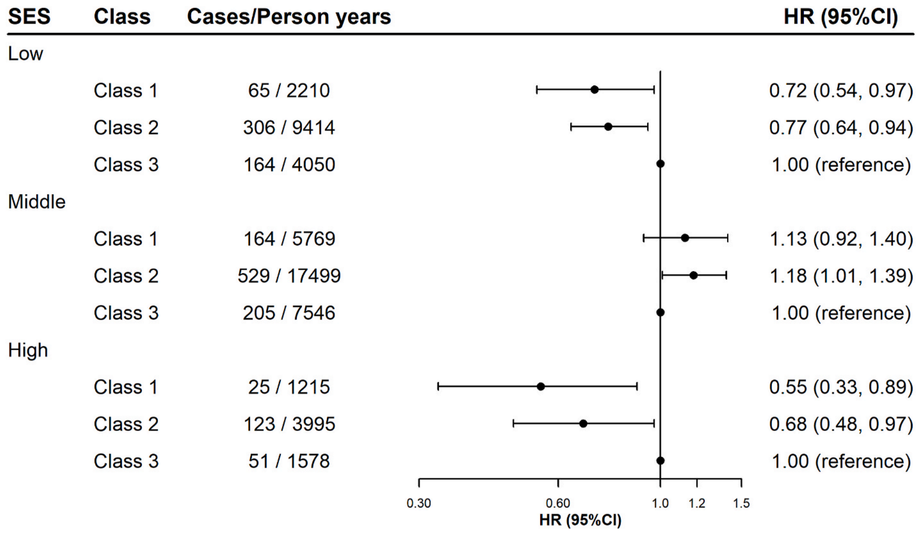

Fig. 2. Hazard ratio (HR) and 95% confidence interval (CI) of all-cause mortality between built environment class stratified by socioeconomic status (SES; low, 1–3; middle, 4–6; high, 7–10). The Cox proportional hazards model was used to estimate HR (95%CI) of Class 1 and Class 2 (compared with Class 3) after being adjusted for age, sex, marital status, education level, alcohol drinking, smoking, number of chronic diseases, Instrumental Activities of Daily Living score, body mass index, waist to hip ratio, physical activity, and Mini-Mental State Examination score. We found a significant interaction of built environment class with SES ($P = 0.001$).

5. Conclusions

In conclusion, in this prospective cohort study of elderly Hong Kong Chinese, 3 certain BE classes were identified from 10 objective BE characteristics using LPA. We found the associations between BE class and all-cause mortality were modified by SES, and people living near greater coverage of building ground coverage and commercial land use (Class 1), and greater open space and proportion of residential land use (Class 2) had a lower all-cause mortality risk compared with those living near greater green space (Class3) among both low- and high-SES people, while among middle-SES people, those who lived near greater open space and proportion of residential land use (Class 2) had higher mortality risk than people living near greater green space (Class 3). Our findings suggest that combinations of multiple BE characteristics should be considered in urban design, and if the BE pattern has a varied effect on mortality risk for different SES groups, then meaningful involvement of diverse groups should also be considered. Further studies are warranted to replicate our findings.

Author contributions

Jiesheng Lin: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Visualization. Jason Leung: Investigation, Data curation, Writing – review & editing, Visualization. Blanche Yu: Investigation. Jean Woo: Investigation, Resources, Writing – review & editing, Visualization. Timothy Kwok: Investigation, Resources. Kevin Ka-Lun Lau: Conceptualization, Methodology, Writing – review & editing, Visualization, Supervision, Funding acquisition.

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Ethics statement

The study was approved by the Clinical Research Ethics Committee in the Chinese University of Hong Kong, and all participants provided written informed consent.

Declaration of competing interest

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

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Appendix A. Supplementary data

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