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Effects of neighborhood building density, height, greenspace, and cleanliness on indoor environment and health of building occupants

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ABSTRACT

The influences of indoor environment quality on occupant health have long been one of the main focuses in built environment and public health research. However, evidence to this effect has been inconsistent. Furthermore, previous urban studies have indicated the interaction between urban morphology and indoor environment. This study thus goes beyond indoor environment to investigate: i) the effects of neighborhood environment on occupant health; and ii) the mediating roles of indoor environment on the neighborhood environment and occupant health relationships. To achieve this aim, buildings located in different neighborhood environment in Hong Kong are selected. Data are collected by post-occupancy evaluation (occupant health), indoor environment assessment (thermal comfort, indoor air quality, ventilation, visual comfort, and acoustic comfort) and neighborhood environment assessment (neighborhood building density, building height, cleanliness and greenspace) through questionnaire survey. Through correlation analysis, regression modelling and Sobel test, it is found that: i) occupant health is significantly affected by neighborhood building height, building density and cleanliness; ii) the relationships between neighborhood environment and occupant health are significantly mediated by indoor environment, in terms of visual and acoustic comfort; and iii) neighborhood greenspace affects occupant health indirectly through influencing indoor air quality. To cross validate the results of the survey study, which is conducted using subjective data, objective measurements and analyses are further conducted. The objective study, echoing the survey study results, indicates that buildings with lower neighborhood building density and height, and cleaner neighborhood environment have better visual (higher illuminance level) and acoustic (lower noise level) performances.

1. Background

Buildings are often designed and developed based on various regulations and guidelines established with an attempt to maintain occupants' comfort within an indoor environment [for instance, compliance with design requirements for ventilation, sustaining indoor air temperature at design values, and maintaining background noise levels within prescribed criteria]. However, building occupants are not isolated from its neighborhood environment. Buildings serve not only to shelter occupants from adverse outdoor environment and weather; but also bring favorable natural elements, such as natural lighting and fresh air, into occupants' work and life. Permeability is one of the key features in any buildings (e.g., [55]. It is this permeability nature which puts occupants of a building and its neighborhood environment into connection. Therefore, the impact of neighborhood environment is a key factor which cannot be overlooked when studying occupant health and indoor environment.

In fact, the effect of indoor environment quality on occupant health has long been an important topic in built environment research and practices. However, the results to these effects have been inconsistent. For instance [57], indicated that occupants' asthma and respiratory allergies are affected by indoor air quality, temperature, humidity and ventilation of an indoor building environment. Similarly [58], and [8] found that occupants' respiratory and asthmatic symptoms are predicted by poor indoor air quality and ventilation. However [41], found that indoor air quality can have both positive and negative effects on occupants' wheeze [22]. found that air quality is not correlated with students' health problems in terms of respiratory symptoms, headache and gastrointestinal symptoms.

The above inconsistent findings, to certain extent, indicate that the relationship between indoor environment and occupant health may be subject to other key factors. Given that neighborhood environment can influence indoor environment (e.g., the influence of neighborhood building density on indoor temperature; [46], it is reasonable to

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postulate that indoor environment can be the mediator of the relationships between neighborhood environment and occupant health. However, it is unclear what and how neighborhood environment factors affect indoor environment and occupant health. Hence, this study goes beyond indoor environment to identify what neighborhood environment factors affect occupant health and indoor environment quality; investigate the influence of these neighborhood environment factors on occupant health; and to examine the impact and interplay of indoor building environment and neighborhood environment on health of building occupants. It is hypothesized that: i) occupant health is significantly affected by a building's neighborhood environment; and ii) the impact of neighborhood environment on occupant health is mediated by indoor environment.

2. Indoor environment and occupant health

Previous studies have identified various indicators for indoor environmental quality, including indoor air quality (IAQ), thermal comfort, ventilation, visual condition, and acoustic condition. *IAQ* refers to the air quality within and around buildings and structures, and it is especially related to health and comfort of building occupants. It can be determined by the concentration of different air pollutants, such as carbon monoxide, nitrogen dioxide, sulphur dioxide, volatile organic compounds, ozone, nonmethane hydrocarbons, particulates sulphates and nitrates, formaldehyde and radon, in an indoor environment [67]. Previous studies have indicated that poor IAQ can cause bronchoconstriction, asthma symptoms, lung cancer, irritation to eyes, visibility problems, headaches, dizziness and even fatal poisoning in occupants (e.g., [19,50]. Since people spend around 90% of their time indoors, IAQ has long been a key focus in different building performance assessments [30].

When comparing with other indoor environment quality indicators, such as acoustic comfort, visual comfort, and IAQ, *thermal comfort* has been ranked by building occupants as of greater importance [17]. Thermal comfort refers to the state of mind that expresses satisfaction and subjective evaluation of the thermal environment [1]. Human body has a thermoregulatory system which serves to maintain a constant internal body temperature [71]. Mediated by the physics of heat and mass transfer in the process of heat balance, people respond physiologically to any thermal imbalance between the body and the surrounding environment. Previous studies have indicated that thermal environment is associated with occupants' well-being, in terms of asthma and respiratory allergies [57].

Ventilation, referred as the air movement within a building, is closely related to IAQ and occupants' thermal comfort [72]. Poor ventilation has been identified as an antecedent of various respiratory diseases, such as severe acute respiratory syndrome (e.g., [18,64]. There are three main types of ventilation, namely mechanical, natural, and hybrid. Mechanical ventilation can cause energy efficiency problem; while natural ventilation is constrained by neighborhood environment. Hybrid ventilation functions to exploit the benefits of both natural and mechanical ventilation methods.

Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" [14], which can usually be affected by two components, namely natural and artificial lighting. Proper control of glare and shading is needed to minimize the impact of excessive or inadequate lighting on occupants' health, including fatigue and eye health, such as watery eyes, dry eyes, eye ache and tired eyes [24]; [47]. In addition, ***acoustic comfort*** refers to the subjective noise annoyance experienced by an individual, which may further affect one's health and cognitive performance [26]. Though individual's acceptance and response to sound pressure and acoustic patterns is subjective, previous studies have proven the impact of noise on individuals' psychological health and memory [5,57].

3. Neighborhood environment and building occupants

The above section indicates the intimate associations between indoor environment and occupants' health. However, indoor environment quality are intimately associated with its neighborhood environment. For instance, previous studies have indicated the impact of urban neighborhood characteristics, in terms of land-use ratio and thermal mass, on indoor air temperature of buildings [43]. On the other hand, air pollutants emitted from vehicles in busy district may cause greater indoor air pollution through permeable building façade [19,52]. Hence, it can be postulated that health of occupants should not only be affected by the indoor environment. It is essential to investigate the interplay of indoor and outdoor environment and their impacts on occupants' health.

According to the previous studies on built environment at neighborhood scale, built environment can generally be categorized into four fields, namely buildings, open spaces (e.g., greenspaces, sidewalks, parking, etc.), mobility (e.g., passenger car, train, bus, etc.) and networks (e.g., electricity, water, wastewater, gas networks, etc.) [38]. While neighborhood networks and mobility are mainly associated with energy consumption, this study, focusing on occupant health, covers the first two fields, buildings and open spaces. The building category refers to both height and density of the buildings nearby, while open spaces refer to neighborhood greenspace and cleanliness of the surrounding area.

Due to the rapid business development and the issue of land scarcity, various modern cities, like Hong Kong, Tokyo, Singapore, and Shanghai, have undergone land use intensification and adopted vertical development strategy in the past decades [9,73]. This has resulted in an increase in building density (site coverage of buildings over a certain area), increase in building height (from the mean formation level of the land on which the building stands, up to the top of the highest roof slab of the main roof of a building), and reduction in open spaces and pollution in urban areas.

To prevent adverse urban environmental and social problems, many countries have adopted different regulations on building density and height, such as restrictions on lot size zoning, building height and plot ratio (e.g., [9,28]. However, along with the rapid development of construction and building services technologies, many cities have increased the maximum permitted building density and height [9,48]. In fact, previous studies have indicated the impact of neighborhood **building height** on the access of sunlight and solar radiation (e.g. [51], indoor temperature [42], dispersion of atmospheric pollutants [62], etc., of a building. On the other hand, high neighborhood **building density** can cause heat island effect, resulting in lower wind speeds and higher ambient temperatures inside a building [46].

The existence of **greenspace** in neighborhood environment, such as tree canopy, parks and forests, has found to be associated with better physical health, reduction in morbidity in some disease categories, lower level of depression, lower level of stress, and so on (e.g., [4]; [70]. In fact, the roles of greenspace have found to be especially significant in protecting building occupants from health hazards related to air pollution and extreme temperature (e.g. [11], and in promoting healthy behaviors amongst building occupants, such as physical activities (e.g., [44,66].

In addition, neighborhood **cleanliness** has been recognized as one of key issues facing policy makers when planning and developing cities [10]. It can cover cleanliness of streets, sidewalks, and footpaths surrounding a building (e.g., existence of debris and graffiti; [29]. Previous studies found that neighborhood cleanliness can affect occupants' satisfaction and health through various factors, like influencing people's willingness to conduct physical activities (e.g., [13,33].

Based on the above, the conceptual model of the study is developed in Fig. 1. As illustrated in the figure, neighborhood environment is hypothesized to predict occupant health (H1); and the influence of neighborhood environment on occupant health is hypothesized to be

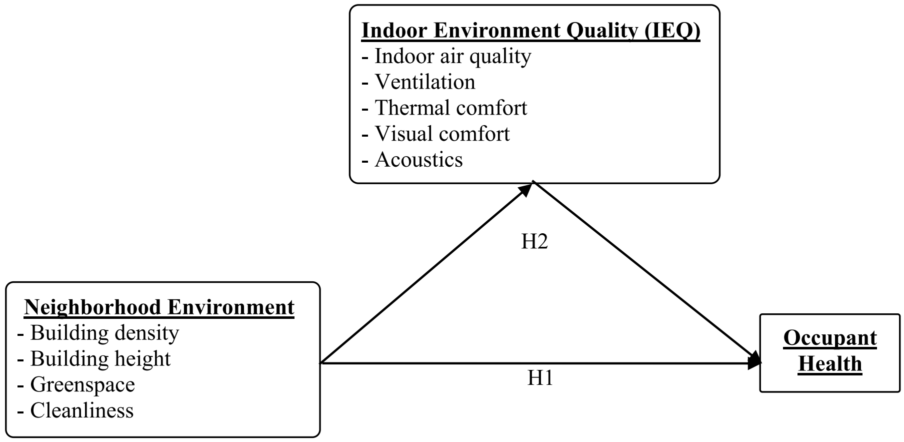

Fig. 1. Hypothetical model of neighborhood environment - IEQ - health of building occupants.

mediated by indoor environment quality (H2).

4. Research methods

To achieve the research aim, we conducted a questionnaire survey study targeting occupants of four academic buildings located in different neighborhood environment in Hong Kong. These four buildings are strategically selected to involve those located in high (two) versus low (two) neighborhood building density, high (two) versus low (two) neighborhood building height, and large (two) versus small (two) neighborhood greenspace. Please refer to Figs. 2 and 3 for the locations of the buildings.

Academic buildings are selected mainly for two reasons. Firstly, unlike commercial buildings which only accommodate the working age groups and residential buildings which accommodate residents with similar social background (e.g., housing affordability), academic buildings accommodate a good mix of occupants who come from different age (e.g., teenage students, senior students, middle aged staff, senior staff, etc.) and social (e.g., students needing financial aid have the same right as students who come from higher income families to enjoy education at universities) groups. On the other hand, previous studies have indicated the intimate relationships between property values and neighborhood environment, such as greenspace (e.g., [27,56]. In other words, occupants of buildings located in a greener environment may have a higher housing affordability, and thus social background, in which these have found to have impact on individuals' health [63]. To ensure a good mix of respondents, this study targets academic buildings which accommodate occupants with different age and social background, and are located in areas with different neighborhood environment.

Previous studies, using academic buildings as the bases of data collection for investigating interactions between occupants and built environment, tend to sample students only (e.g., [40]. In view of the

Fig. 2. Two buildings in a neighborhood.

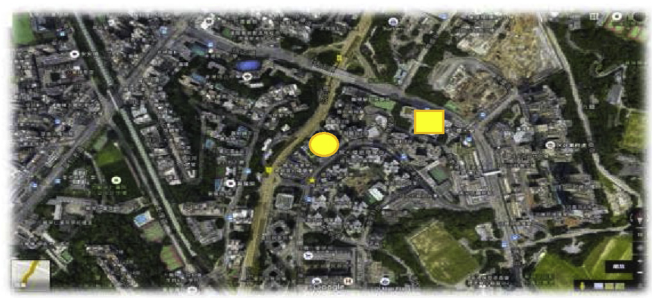

Fig. 3. Two buildings in a neighborhood. environment with lower building density, environment with higher building density, lower building height and larger green higher building height and smaller green space. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

potential impact of respondents' age on health and satisfaction, this study targets not only students, but also academic and administrative staff. Purposive sampling is adopted, in which respondents are recruited only if they are academic or administrative staff working or students studying in the target academic buildings. In sum, 200 valid responses are collected. Students account for 64.5% of the total sample, while academic and administrative staff account for 35.5%. The respondents age from 30 or below (71.5%), 31–50 (26%), to 50 or above (2.5%), in which 57.5% are male and 42.5% are female. Amongst the respondents, 56% spent 11–30 h in the building a week, 36.5% spent more than 30 h and 7.5% spent 10 h or less. To control the impact of building age on occupants, the target buildings are 4–9 year-old (built in the past decade), with 25% aged 4, 25% aged 5, and 50% aged 9.

The post-occupancy evaluation survey is designed to have four main parts, namely, background information, indoor environment quality (indicated by occupants' satisfaction towards indoor air quality, ventilation, thermal comfort, lighting, and acoustics; [7], neighborhood environment quality (indicated by occupants' satisfaction towards neighborhood building density, building height, greenspace and cleanliness [16], and building-related health symptoms (frequency of occupants suffering from dry eyes, itchy or watery eyes, blocked or stuffy nose, runny nose, dry throat, lethargy or tiredness, headaches, dry, itching or irritated skin, sneezing, and breathing difficulties; [53]. Adopting the health measurement scale developed by Ref. [53]; respondents were asked to rate the frequency of the 10 symptoms. Occupant health is then calculated by taking an average of the scores of these 10 items. Respondents were invited to answer the questions based on a 7-point likert measurement. Statistical analyses are then conducted, using the software of SPSS, to investigate the hypothetical relationships between neighborhood environment, indoor environment,

Table 1
Correlation of neighborhood environment, indoor environment and occupant health.

Indoor Environment & Occupant Health Neighborhood Environment	Thermal Comfort	IAQ	Ventilation	Visual Comfort	Acoustic Comfort	Occupant Health
Neighborhood Bldg Density	.456**	.297**	.365**	.348**	.348**	.335**
Neighborhood Bldg Height	.304**	.275**	.263**	.427**	.424**	.404**
Neighborhood Greenspace	.410**	.515**	.433**	.406**	.341**	.356**
Neighborhood Cleanliness	.316**	.334**	.334**	.431**	.256**	.315**

Note: ** - significant at 0.01 level.
All analyses are controlled for age and gender.

and health of occupants.

5. Analyses and results

5.1. Survey study

Since health differs according to individual occupants' background characteristics, this study, making references to previous studies on occupant health, statistically controls for gender and age of occupants in the correlation and regression analyses (e.g., [63].

5.1.1. Correlation analysis

To preliminarily investigate the relationships between neighborhood environment, indoor environment and occupant health, Pearson correlation analysis was conducted (see Table 1). The results indicate that all four neighborhood factors correlate significantly with the five indoor environment factors and occupant health. All correlation coefficients are significant at $p < 0.01$ level. The results act as a solid foundation for further testing the predicting effect of neighborhood environment on occupant health, and the mediating effects of indoor environment on neighborhood environment-occupant health relationships.

5.1.2. Regression modelling

To further investigate the predicting effects of neighborhood environment on occupant health, multiple regression modelling was conducted. Based on the result of Pearson correlation, all four neighborhood environment factors are significantly correlated with occupant health. They are thus all selected as independent variables in the multiple regression analysis with occupant health as dependent variable. As shown in Model 1 of Table 2, neighborhood building height, neighborhood building density and neighborhood cleanliness are found to predict occupant health significantly ($p < 0.05$). The model explains 24.3% of variance to occupant health. H1 is thus supported. The results also act as a basis for the following mediation tests.

A mediator is referred to as a variable which accounts for the relation between an independent variable and a dependent variable. To measure the mediating effects of indoor environment (i.e., thermal comfort, indoor air quality, ventilation, visual comfort and acoustic comfort) on the relationships between neighborhood environment (i.e., neighborhood building height, neighborhood building density, neighborhood greenspace and neighborhood cleanliness) and occupant health, the classic Sobel test is adopted [2]. The Sobel test involves three main steps [2]: Step A-to show that the independent variable (i.e., neighborhood environment) significantly affects the dependent variable (i.e., occupant health) in the absence of the mediator; Step B— to show that the independent variable significantly affects the mediator (i.e., indoor environment); and Step C— to show that the independent variable and the mediator have significant effects on the dependent variable. While Step A is done as shown in Model 1 for the first hypothesis of the current study, Steps B and C are done in the following regression analyses.

Step B is then conducted as shown in Models 2–6 in Table 2, where the five indoor environment factors are included in each model as a dependent variable, and the four neighborhood environment factors are added as independent variables in each model respectively. The results indicate that neighborhood building density significantly predicts thermal comfort, ventilation, and acoustic comfort ($p < 0.01$). Neighborhood building height significantly predicts visual comfort and acoustic comfort ($p < 0.01$). Neighborhood greenspace significantly predicts thermal comfort, indoor air quality, and ventilation ($p < 0.01$). Lastly, neighborhood cleanliness predicts visual comfort significantly ($p < 0.01$).

Model 7 is further developed to investigate, with the absence of the effects of the neighborhood environment, the predicting effects of the five indoor environment factors on occupant health. The results indicate that occupant health is significantly predicted by acoustic comfort, indoor air quality and visual comfort ($p < 0.01$). The model explains 35.7% of variance to occupant health.

Then, Step C is conducted as shown in Models 8–11 in Table 3. Models 8–11 are developed with occupant health as dependent variable and with a different combination of an indoor environment and a neighborhood environment as independent variables for each model. The combinations are determined based on the significant associations found in Models 2–6 as shown in Table 2. As shown in Table 3, occupant health is significantly predicted by both indoor environment (i.e., visual comfort or acoustic comfort) and neighborhood environment (i.e., neighborhood building density, neighborhood building height and neighborhood cleanliness) in the four models respectively ($p < 0.01$).

The regression coefficient estimates and the standard error of the paths from independent variable to mediator (i.e. ‘a’ and ‘ta’ from Models 2–6) and from mediator to dependent variable (i.e. ‘b’ and ‘tb’ from Models 8–11) are then obtained. Then, the Sobel z-value are calculated through dividing ab by the square root of b2 (a/ta) 2 + a2 (b/tb) 2. The mediating effect is considered to be significant at the 0.05 level if the z-value is larger than 1.96 in absolute value. As shown in the last column of Table 3, all four mediation effects are found to be significant (i.e., > 1.96). Thus, H2 is also supported.

The abovementioned significant associations are illustrated in Fig. 4.

5.2. Field study for objective measurements

Fig. 4 illustrates that health of occupants is influenced by *neighborhood building density, neighborhood building height* and *neighborhood cleanliness*, and these influences are mediated by indoor environment quality, in terms of *acoustic comfort* and *visual comfort*. However, previous studies indicate that human comfort level in a built environment can be affected by various psychological parameters, such as individuals' desired condition [40] and environmental beliefs [12]. To validate whether neighborhood environment does contain objective effects on indoor acoustic and visual levels, a field measurement study is further conducted.

Firstly, the four target buildings are categorized into two groups, in which ***Group 1*** represents buildings located in a *neighborhood environment with lower building density, lower building height, and better neighborhood cleanliness*; while ***Group 2*** represents buildings located in a *neighborhood environment with higher building density, higher building height, and poorer neighborhood cleanliness*.

The differences in neighborhood building density and height of

Table 2
Development of base models.

Model	Dependent variables	Independent variables	Beta		t	Sig.	R	R^2	Sig. (ANOVA)
			UnSTD	S.E.					
Occupant Health ← Neighborhood Environment									
1	Occupant Health	(Constant)	28.880	3.691	7.824	.000	.493	.243	.000
		Neighborhood Building Height	1.798	.497	3.615	.000			
		Neighborhood Building Density	1.137	.525	2.165	.032			
		Neighborhood Cleanliness	1.237	.583	2.122	.035			
Indoor Environment ← Neighborhood Environment									
2	Thermal Comfort	(Constant)	15.992	.866	18.471	.000	.504	.254	.000
		Neighborhood Building Density	.858	.176	4.885	.000			
		Neighborhood Greenspace	.363	.108	3.388	.001			
3	Indoor Air Quality	(Constant)	20.361	.559	36.442	.000	.529	.280	.000
		Neighborhood Greenspace	.747	.088	8.441	.000			
4	Ventilation	(Constant)	7.514	.622	12.080	.000	.467	.218	.000
		Neighborhood Greenspace	.360	.077	4.674	.000			
		Neighborhood Building Density	.350	.126	2.770	.006			
5	Visual Comfort	(Constant)	19.106	1.193	16.021	.000	.511	.261	.000
		Neighborhood Cleanliness	.955	.208	4.586	.000			
		Neighborhood Building Height	.760	.169	4.504	.000			
6	Acoustic Comfort	(Constant)	15.877	1.019	15.588	.000	.462	.213	.000
		Neighborhood Building Height	.786	.167	4.694	.000			
		Neighborhood Building Density	.517	.181	2.849	.005			
Occupant Health ← Indoor Environment									
7	Occupant Health	(Constant)	4.036	5.298	.762	.447	.597	.357	.000
		Acoustic Comfort	.952	.201	4.745	.000			
		Indoor Air Quality	.627	.203	3.087	.002			
		Visual Comfort	.435	.184	2.365	.019			

Note: All analyses are controlled for age and gender.

Groups 1 and 2 buildings are illustrated in Figs. 2 and 3 respectively. In fact, the number of neighborhood buildings and average building height within 1 km distance from Group 1 buildings (11 buildings with 13 storey on average) are lower than that of Group 2 buildings (44 buildings with 15 storey on average).

To further explore whether significant differences in neighborhood cleanliness exists between Groups 1 and 2 buildings, one-way between-groups analysis of variance (ANOVA) was conducted using the survey data. Respondents from Group 1 buildings (Mean = 6.2) are found to have significantly higher satisfaction towards neighborhood cleanliness when compared with that of the respondents from Group 2 (Mean = 5.33) buildings [$F = 26.810$, $p < 0.01$].

Hence, the following comparative analyses are conducted using Groups 1 and 2 buildings as analysis units, representing buildings with different levels of neighborhood building density, height and cleanliness.

The survey study unveils that neighborhood environment influences occupant health via two indoor environment factors, namely acoustic and visual comfort. Therefore, in this section, the performance of the two groups of buildings in these two dimensions are measured objectively on site. Since acoustic and luminance levels deviate from time to time throughout a day, measurements were conducted on an hourly basis, from 09:00am to 06:00pm. MINOLTA Lux meter was used to measure the illuminance level, and ONO SOKKI LA-5110 Precision Integrated Sound Level Meter was used to measure the noise level.

5.2.1. Acoustic performance analysis

In general, noise level in office buildings is recommended to be lower than ~50 dB. For instance, the Chinese code for sound insulation design for civil buildings recommended that the noise level in office buildings should be lower than 55 dB. The Building Environmental Assessment Method (BEAM) Plus noise performance criteria for office premises recommends 48 dB for office areas where privacy is important. Furthermore, a previous study found empirical support that office

Table 3
Regression modelling for the mediating effect of indoor environment on neighborhood environment-occupant health relationships.

Model	Dependent variables	Independent variables	Beta		t	Sig.	R	R^2	Sig. (ANOVA)	Sobel
			UnSTD	S.E.						
Occupant Health ← Neighborhood Environment & Indoor Environment										
8	Occupant Health	(Constant)	16.695	4.167	4.006	.000	.563	.317	.000	2.64**
		Acoustic Comfort	1.269	.182	6.957	.000				
		Neighborhood Building Density	1.255	.464	2.703	.007				
9	Occupant Health	(Constant)	17.602	4.017	4.381	.000	.577	.332	.000	3.77**
		Acoustic Comfort	1.170	.186	6.279	.000				
		Neighborhood Building Height	1.511	.438	3.450	.001				
10	Occupant Health	(Constant)	20.097	4.834	4.157	.000	.516	.266	.000	3.10**
		Visual Comfort	.781	.183	4.257	.000				
		Neighborhood Building Height	1.846	.460	4.015	.000				
11	Occupant Health	(Constant)	18.794	5.061	3.713	.000	.477	.228	.000	3.32**
		Visual Comfort	.902	.188	4.788	.000				
		Neighborhood Cleanliness	1.386	.583	2.379	.018				

Note: ** - significant at 0.01 level.
All analyses are controlled for age and gender.

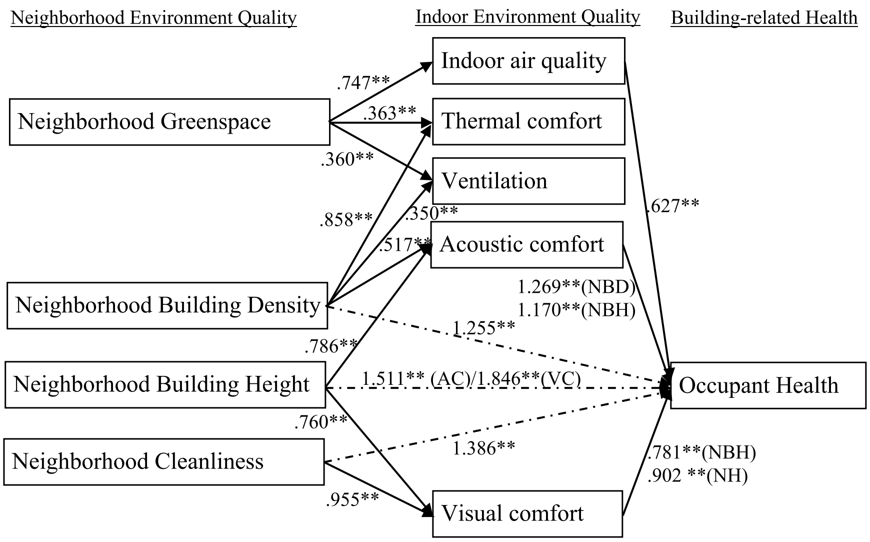

Fig. 4. The result model for indoor environment, neighborhood environment and health (refer to Tables 2 and 3 for the coefficients of each relationship).
Note:- →Significant mediating effects (refer to Table 3)- (xxx) contribution of the bracketed variable being taken into account in the mediating process- NBD – Neighborhood Building Density- NBH – Neighborhood Building Height- NH – Neighborhood Cleanliness- AC – Acoustic Comfort- VC – Visual Comfort

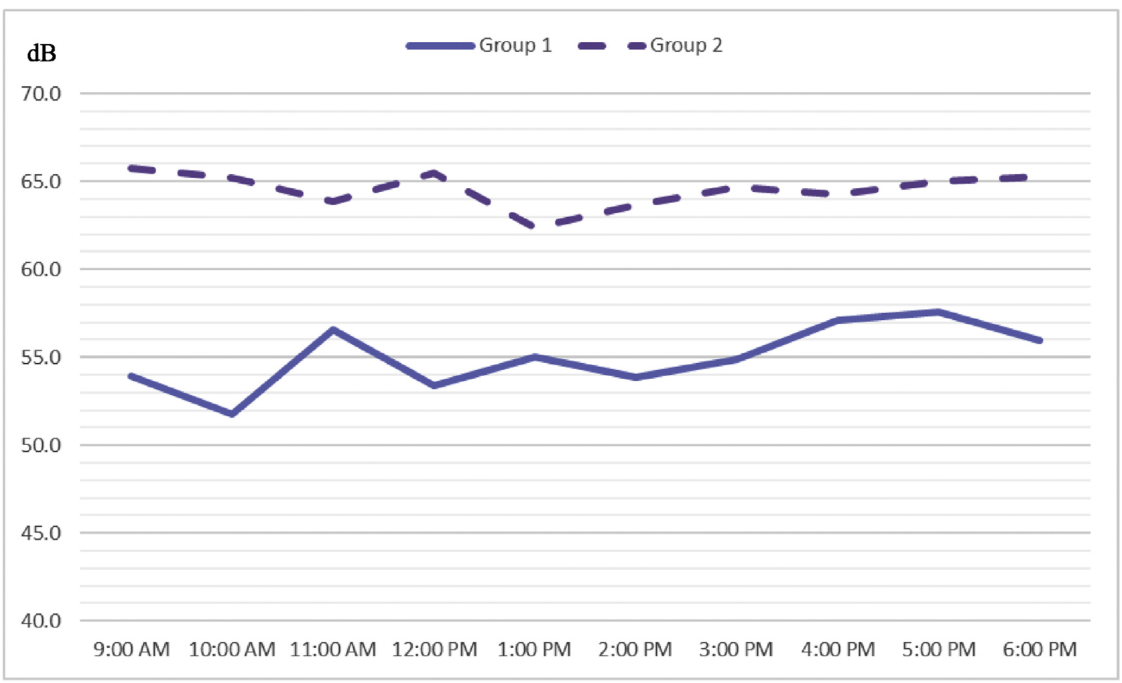

Fig. 5. Comparison of noise level between Groups 1 (lower building density, building height, and better neighborhood cleanliness) & 2 (higher building density, building height, and poorer neighborhood cleanliness) buildings.

building occupants are satisfied when noise level is below 49.6 dB [25]. However, as illustrated in Fig. 5, during the work hours, the noise levels of Groups 1 and 2 buildings are all above 50 dB. For Group 1, the noise levels range from 51.8 dB to 57.6 dB. For Group 2, the noise levels range from 62.4 dB to 65.8 dB. On average, the noise level of Group 1 is 55 dB, just meeting the upper limit as recommended by the Chinese code; while that of Group 2 is 64.5 dB, which is far above the upper limits as suggested by various code or guidelines. The above, conforming to the results of the survey study, indicates that the acoustic performance of Group 1 (buildings located in a neighborhood environment with lower building density, lower building height, and better neighborhood cleanliness) is better than Group 2 (buildings located in a neighborhood environment with higher building density, higher building height, and poorer neighborhood cleanliness).

5.2.2. Illuminance performance analysis

Previous studies have found empirical support that the higher the illumination intensity, the higher the occupants' satisfaction level of the luminous environment (e.g., [35]. Furthermore [25], indicates that occupants start to feel satisfied when the illumination intensity is above 300 Lux, and the satisfaction level increased to ‘quite satisfied’ when the light level reached 1000 Lux. As illustrated in Fig. 6, during the work hours, the illuminance levels of Groups 1 and 2 buildings are all above 400 Lux. On average, the illuminance level of Group 1 is 529 Lux, while that of Group 2 is 434 Lux. The above, conforming to the results of the survey study, indicates that the illuminance performance of Group 1 (buildings located in a neighborhood environment with lower building density, lower building height, and better neighborhood cleanliness) is better than Group 2 (buildings located in a neighborhood environment with higher building density, higher building height, and poorer neighborhood cleanliness).

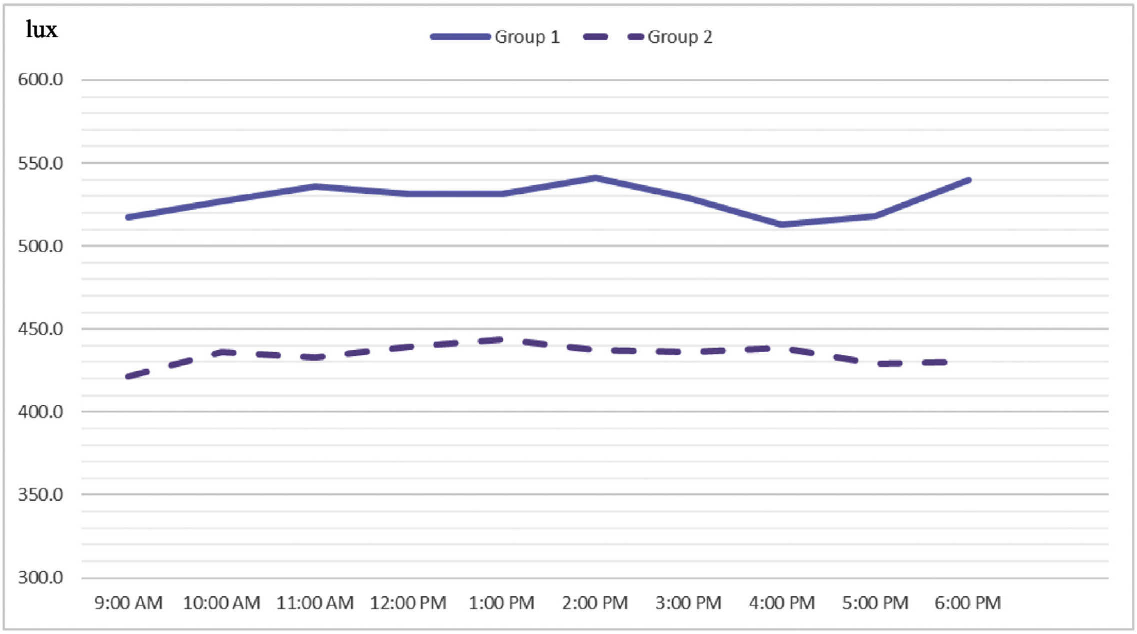

Fig. 6. Comparison of illuminance level between Groups 1 (lower building density, building height, and better neighborhood cleanliness) & 2 (higher building density, building height, and poorer neighborhood cleanliness) buildings.

5.3. Comparative analysis for occupant health of groups 1 and 2 buildings (T-test based on subjective data)

To investigate whether statistically significant differences exist between health of occupants from the two groups of buildings, an independent-samples *t*-test was conducted based on the survey data using SPSS. Significant differences are found in occupant overall health ($p = 0.00$), and various health symptoms, namely dry eyes ($p = 0.001$), itchy or watery eyes ($p = 0.012$), blocked or stuffy nose ($p = 0.003$), runny nose ($p = 0.000$), dry throat ($p = 0.000$), lethargy or tiredness ($p = 0.001$), dry, itching or irritated skin ($p = 0.049$), and sneezing. The mean values are shown in Fig. 7.

6. Discussion & implications

The results of this study indicates that health of occupants are directly affected by neighborhood building density, neighborhood building height and neighborhood cleanliness, and these effects are significantly mediated by occupants' acoustic and visual comforts in the indoor environment. Meanwhile, even though neighborhood greenspace is found to have no direct impact on occupant health, it has found to have indirect impact on occupant health through its influence on indoor air quality (refer to Fig. 4). The survey results are further confirmed by the objective study which indicates that the acoustic and illuminance performance of buildings with lower neighborhood building density, lower neighborhood building height and cleaner neighborhood

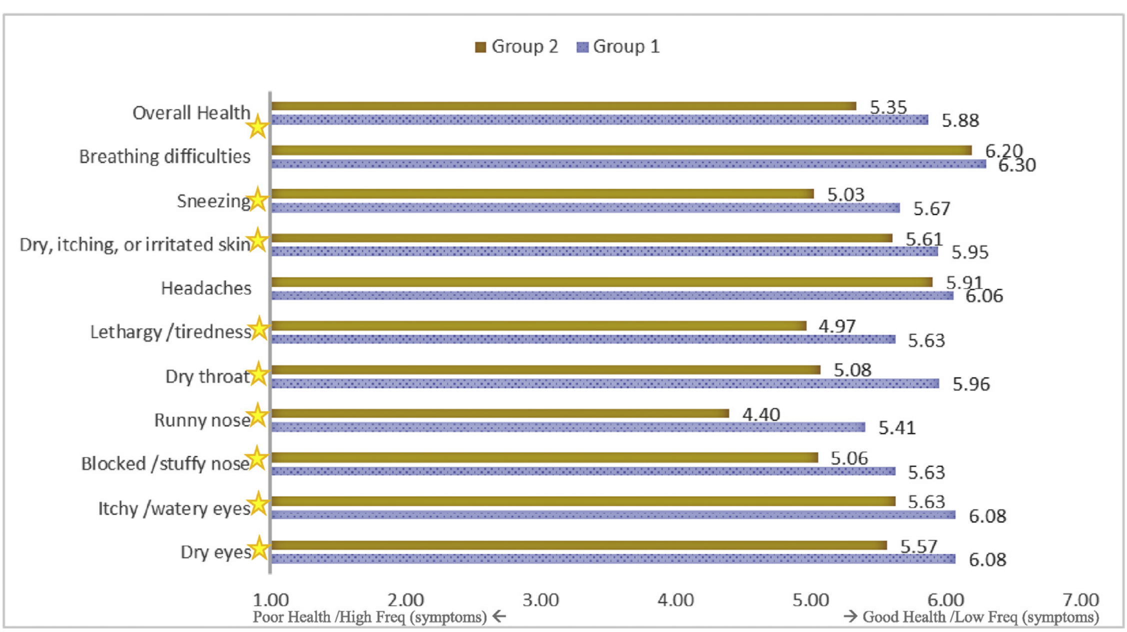

Fig. 7. Comparison of health between occupants of Groups 1 (lower building density, building height, and better neighborhood cleanliness) & 2 (higher building density, building height, and poorer neighborhood cleanliness) buildings. Note: A star denotes significant difference found in *t*-test ($p < 0.05$).

area are better that of their counterparts.

The impact of **neighborhood building height** on occupant health is significantly mediated by occupants' ***visual comfort*** in the indoor environment. Occupants' visual comfort can be affected by indoor lighting quality (e.g. [24], natural lighting, and bright reflection of visible light from concrete roof and /or from the facades of neighborhood buildings (e.g., [61]. High-rise neighborhood buildings can act as obstructions, resulting in insufficient natural lighting in the indoor environment. Hence, as indicated in the objective measurement study, the illuminance level of Group 1 buildings is higher than that of Group 2 (refer to Fig. 6). On the other hand, a low-rise neighborhood area can also mean lesser reflection of light from the roofs and facades of neighborhood buildings, reducing the impact of outdoor glare on indoor lighting quality. Extreme light levels can cause eye health problems to building occupants [24], however, its impact can be reduced if a building is equipped with an effective design strategy and lighting system, such as the adoption of façade design with visible light transmittance glazing and smart lighting system with light sensors, which enhance occupants' visual comfort (e.g., [32,39].

On the other hand, the impact of **neighborhood cleanliness** on occupant health is also significantly mediated by occupant's indoor ***visual comfort***. Previous studies have found that people living nearby pollution sources, like industrial areas, have a higher risk on air-quality related diseases, such as lung cancer (e.g., [23]. However, neighborhood cleanliness is found to have no direct association with indoor air quality or ventilation in the current study. Perhaps, it is the dissatisfactory visual appearance of pollutants, such as debris and graffiti, in the neighborhood environment, which causes poor health of occupants [32].'s study indicated how occupants managed to address visual discomfort resulting from excessive sunlight due to an inappropriate building design through various informal workspace modifications, such as using umbrella to block the connection with outdoor lighting. Hence, it is recommended to manage visual discomfort caused by poor neighborhood cleanliness using different space modifications, such as curtain blocking outside views to a certain level.

The impacts of **neighborhood building density and height** on occupant health are significantly mediated by occupants' ***acoustic comfort*** in the indoor environment. Excessive noise can cause building occupants to heart diseases, lower concentration level, and so on [25,36]. In developed cities, like Hong Kong, transport noise, such as road traffic and railway noise, is the major source of noise affecting building occupants [38]. In this case, neighborhood buildings can act as obstructions to the free propagation of noise from street and road traffic, attenuating its sound level [21]. In current study, since the two Group 2 buildings are located right next to two main roads, with the absence of neighborhood buildings serving as sound obstructions, Group 2 buildings are found to have higher noise levels than that of Group 1 buildings. Enhancing sound insulation level of a building can reduce the level of sound energy emitted from the neighborhood environment entering its inner space, thus, enhancing occupant acoustic comfort and relieving the significant impact of outdoor noise to occupants.

Various previous studies indicated that **neighborhood greenspace** affects building occupant health. Researchers tend to associate this result with the opportunity provided to occupants to walk and exercise (e.g., [44,66]. In current study, even though half of the buildings are located in areas surrounded by large greenspace, majority of these green areas are not accessible (fall outside the premises area) (refer to Fig. 8).

As such, neighborhood greenspace is found to have no direct impact on occupant health in the current study. However, it significantly affects ***indoor air quality***, which further influences occupant health. A larger area of neighborhood greenspace can, to certain extent, mean a lower number of neighborhood buildings. Neighborhood buildings can act as obstacles to fresh air moving into a building. This blocking effect would be higher if a building is surrounded by denser and taller neighborhood buildings. The reduced level of indoor air ventilation can slowdown the transfer rate of indoor air pollutants when the indoor pollution concentration is higher than that of the outdoor [3], causing respiratory diseases, eye problems, headaches, and even fatal poisoning (e.g., [19,50]. Hence, the need of an effective ventilation system is essential in fostering occupant health, especially when neighborhood greenspace is not satisfactory.

Fig. 8. Accessible greenspace near the sampled buildings (green areas inside the yellow boundary). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Previous studies tend to focus on the influence of indoor environment on occupants and to study the impact of urban environment on building performance (e.g., the impact of neighborhood building morphology on energy consumption of a building; [68]. The intimate and intertwining relationships between neighborhood environment, indoor environment and occupant health are not clear. Further developed from the results of these previous studies, the current study provides empirical support on the extended effects of neighborhood environment, when interacting with indoor environment, on occupants' health. The findings, to certain extent, indicate that consideration of indoor environment alone does not guarantee a better indoor environment, nor better occupant health. This sheds light to the importance of taking neighborhood environment and its interaction with respective indoor environment indicators into account in building assessment process.

Based on the findings of the current study, building designers and engineers are recommended to put more emphases and weighting on indoor air quality, acoustic comfort and visual comfort of occupants in building design and assessments processes, because these factors are found to have direct effects on occupant health. More importantly, considerations and assessments have to be extended to neighborhood building density (acoustic comfort), neighborhood building height (acoustic and visual comfort) and neighborhood greenspace (indoor air quality) when the above indoor environment quality issues are concerned.

7. Limitations

The sample size of the survey study is comparable to or even larger than some of the published works in the built environment field which use similar mixed method approach (e.g., 88 survey samples collected by Ref. [31]; 120 survey samples collected by Ref. [25]; 200 survey samples collected by Ref. [40]. Meanwhile, the data collection is strategically designed to include respondents with various background (i.e., age, occupation, gender, etc.), occupying in buildings located in different neighborhood environment (i.e., high versus low neighborhood building density and height, large versus small neighborhood greenspace, and good versus poor neighborhood cleanliness).

The survey study adopts a self-report measurement approach, which could have resulted in common method variance. However, it should be noted that the scales in this study are adopted from the extensive literature on built environment and post-occupancy evaluation. In addition, the respondents are all staff and students who have direct, long-term occupancy experience in the case buildings. Furthermore, the current study confirms the significant mediating effects of indoor environment quality on the relationships between neighborhood environment quality and occupants' building-related health symptoms.

Four neighborhood environment factors are included in this study. Even though all of them are found to have significant impact on occupant health and /or indoor environment, it is recommended to include one more neighborhood factor, that is the neighborhood traffic, in the further study. The associations between acoustic comfort and occupant health are found to be affected by neighborhood building density. Even though neighborhood building density can somehow reflect the traffic condition nearby, traffic flow has long been identified as the major source of noise for building occupants. Hence, a further detailed study is recommended to investigate the impact of traffic on the indoor environment quality and occupant health.

Focusing on environment (neighborhood and indoor) and human (satisfaction and health) interactions, the results of the current study provide empirical support on the intertwining relationship between neighborhood environment, indoor environment and occupant health. Based on the study results, further study is recommended to take into account the impact of building configuration and design (e.g., envelops, ventilation system, HVAC system, sound insulation system, etc.) on the environment and human variables.

8. Conclusion

In sum, the study provides empirical support that: i) occupant health is significantly affected by neighborhood building height, neighborhood building density and neighborhood cleanliness; ii) the relationships between neighborhood environment and occupant health are significantly mediated by indoor environment, in terms of visual comfort and acoustic comfort; and iii) even though neighborhood greenspace is found to have no direct impact on occupant health, it affects occupant health indirectly through influencing indoor air quality. The results lay solid platform on the importance of taking neighborhood environment into considerations during building design and assessment stages. Furthermore, the study results also push forward the development of academic research in the field. Researchers have conducted various studies on the impact of indoor environment quality on occupant satisfaction and health. However, evidence to this effect has been inconsistent. This study goes beyond indoor environment to develop the concept of outdoor and indoor environment interaction for revealing the intertwining relationships between neighborhood environment, indoor environment, and health of occupants.

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