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RESEARCH

THE INDOOR ENVIRONMENTAL QUALITY PERFORMANCE OF GREEN LOW-INCOME SINGLE-FAMILY HOUSING

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ABSTRACT

There is little empirical evidence in the literature about the indoor environmental quality performance of residential buildings in general and of social housing in particular. To address this problem, this study used a mixed-method approach to evaluate the indoor environmental quality performance of 17 green low-income single attached family houses in Brandon, Manitoba, Canada. Questionnaires were administered to occupants to assess their snapshot and long-term satisfaction with the indoor environment. In addition, snapshot measurements were carried out to evaluate the indoor environmental quality factors of thermal comfort, indoor air quality, lighting and acoustics. Occupants' snapshot satisfaction was categorized into two groups (i.e. satisfied/comfortable or dissatisfied/uncomfortable) and compared with snapshot measurements. The results showed the measured IEQ parameters were well below recommended threshold levels. Further, occupants with higher snapshot satisfaction were generally exposed to relatively lower levels of indoor pollutants. A statistically significant difference was found in PM_{10} level only between the snapshot satisfied and snapshot dissatisfied groups of occupants. Apparent sound transmission classes were below the standard reference value of 50, suggesting potential problems in noise attenuation within different spaces in each apartment and between apartments. The findings of this study could help governments implement green shadowing for public-housing and also renovate existing houses using the same principles.

KEYWORDS

indoor environmental quality, low-income housing, social housing, green houses, thermal comfort, indoor air quality, lighting, acoustics

1. INTRODUCTION

Approximately 15% of the total population in developed countries live in low-income households characterised by poor indoor environmental conditions such as extremely high or low temperatures and poor ventilation (Santamouris, Pavlou, Synnefa, Niachou, & Kolokotsa, 2007). According to Statistics Canada (2016), nearly 14% of Canadians lived in low-income

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households in 2012, reinforcing the need to improve indoor environmental quality (IEQ) in their homes.

In Manitoba, Canada, a program for sustainable affordable housing for low-income households was initiated by Manitoba Housing and completed in 2010. The program aimed to build low-income green housing that was energy-efficient, used green (i.e. low-emission) building materials, and improved occupants' satisfaction with their indoor environment. Twenty-four of those homes were built in Brandon, Manitoba. The study focused on evaluating the IEQ conditions of those Brandon homes and to assess the inherent relationships between self-assessed IEQ satisfaction and objective measurements of IEQ. This is to address the anecdotal evidence in the literature (Alborz & Berardi, 2015; Ravindu, Rameezdeen, Zuo, Zhou, & Chandratilake, 2015; Y. Xiong, U. Krogmann, G. Mainelis, L. A. Rodenburg, & C. J. Andrews, 2015) about the improved IEQ of green residential buildings. The significance and originality of this study stem from it being the first to assess and provide insight, using objective and subjective methods, on the four main factors of IEQ in residential buildings: thermal comfort (TC), indoor air quality (IAQ), lighting and acoustics. The objective methods included physical monitoring of indoor environmental parameters, whereas the subjective methods involved assessing occupants' satisfaction with their indoor environment using a questionnaire survey. Physical observation of the indoor and outdoor conditions of each home was also carried out on the same day of the physical measurements and questionnaire survey. The findings of this study should provide evidence to inform governments' use of green shadowing for public-housing and to improve engineers and architects' design and building managers' operation of it. This study will also add to the growing body of evidence on the performance of green shadowed residential buildings and contribute to the ongoing debate on how to improve the IEQ conditions of social housing.

2. LITERATURE REVIEW

2.1 The concept of social housing

Even though the precise definition of social or affordable housing can vary, social housing aims in general to achieve one main goal: the provision of housing to low-income or impoverished households and individuals. In North America, social housing is predominantly termed public-housing. Evidence from the literature suggests residents of public-housing tend to be in poorer health than the general population (Theodos, Popkin, Parilla, & Getsinger, 2012). This is because these residents are at higher risk of exposure to indoor environmental pollution in their homes and thus disproportionately affected by chronic environmental diseases including asthma (Breysse et al. (2011). This reinforces the need to elucidate this relationship between housing-related diseases and housing quality to assist governments, community planners and designers in developing public-housing that will enhance its occupants' health (Wu et al., 2007).

2.2 IEQ evaluation of social housing

A review of the literature reveals little empirical evidence on the IEQ of residential buildings in general and of public-housing in particular (McGill, Oyedele, & McAllister, 2015). This is a problem given the socio-economic differences between occupants of public housing and other housing and building types, and the dynamic and complex relationships between socio-economic factors such as the level of income and educational status, and buildings' IEQ (Brown et al., 2015). The literature in the field (e.g. Brown et al., 2015; Kolokotsa & Santamouris, 2015; Paravantis & Santamouris, 2016) suggests that low-income households are at a higher risk of indoor air pollution and other IEQ-related problems for reasons related to both housing quality and personal traits. In some European countries (e.g., the United Kingdom and Greece), a strong link was found between smoking and income levels, with low-income home occupants found most likely to smoke indoors than those in high-income homes (Shrubsole et al., 2016). This likelihood of indoor smoking increased the risk of exposure to environmental tobacco smoke and other indoor air contaminants (Kolokotsa & Santamouris, 2015; Santamouris et al., 2007). Other sources of indoor pollutants such as household chemicals (e.g., indoor sprays, detergents, and disinfectants) were also prevalent in low-income households (Brown et al., 2015; Kolokotsa & Santamouris, 2015). Moreover, overcrowding because of characteristically small low-income dwellings may lead to elevated concentrations of indoor pollutants such as carbon dioxide and thus cause discomfort. This is compounded by a lack of understanding among public housing occupants of how to operate mechanical ventilation systems (McGill et al., 2015). In addition to indoor air pollution, there are other IEQ problems related to thermal discomfort, visual discomfort and high noise levels in low-income households (Krüger & Trombetta Zannin, 2007; Santamouris et al., 2007).

Social intervention programs using sustainable construction principles have been implemented in several countries to address these concerns. In the United States for example, a nationwide weatherization program of low-income family houses led to significant improvements in the IEQ of these homes (Doll, Davison, and Painting, 2016). Similarly, Breysse et al. (2011) reported significant health improvements (i.e. asthma and non-asthma respiratory problems) among adult tenants following the renovation of affordable housing using green principles (e.g. low VOC-adhesives and paints, kitchen and bath exhaust fans). Rojas, Wagner, Suschek-Berger, Pfluger, and Feist (2015b) noticed significant improvements in occupant comfort following the use of passive housing to improve ventilation in low-income houses in Austria.

Despite their value, these studies investigated a limited aspect of IEQ by focusing on assessing either occupants' IEQ satisfaction or TC, IAQ or both with no assessment of acoustics or lighting. There is also very little research on IEQ in residential buildings and green public-housing that uses a combination of subjective and objective methods. Y. Xiong et al. (2015) remarked that the majority of IEQ studies used subjective methods such as interviews and surveys to investigate occupants' perception of their IEQ. This perception may be different from one occupant to another despite these occupants being subjected to the same environmental conditions (Frontczak & Wargocki, 2011). Only a few studies (Langer, Bekö, Bloom, Widheden, & Ekberg, 2015; Rojas, Wagner, Suschek-Berger, Pfluger, & Feist, 2015a; Youyou Xiong, Uta Krogmann, Gediminas Mainelis, Lisa A. Rodenburg, & Clinton J. Andrews, 2015) used objective methods. These studies usually relied on electronic instruments to physically measure parameters related to the IEQ factors of TC or IAQ only. These instruments can be costly, may require calibration and may generate a large amount of data that can be difficult to analyze (Heinzerling, Schiavon, Webster, & Arens, 2013), thus the limited use of objective methods in IEQ studies.

3. MATERIALS AND METHODS

3.1 Study design

Of the 24 apartments in Brandon, occupants of 17 apartments participated in this study. The apartments were located about 100 metres from a major busy road, a railway line and light-industrial buildings. They were also surrounded by ancillary light traffic roads. The apartments were two-storey, with three bedrooms constructed of conventional wood structure. Wall insulation was added to ensure thermal protection to building elements and spaces and to avoid excessive air leakage. The overall window-wall ratio (WWR) of the building was approximately 0.18. The north side of the apartments has maximum WWR compared to relatively minimum WWR in the south side to allow for sufficient daylight with maximum heat gain in the winter and thus optimal balance between energy and daylight. Figure 1 shows the north and south side elevations of the apartments. Each apartment has a gross usable floor area of 141 m^2. All floors, except the bathrooms, were furnished with hardwood board base floor type covered with linoleum finish, while the bathroom floors were furnished with sheet vinyl. The buildings were equipped with green features such as heat recovery ventilators (HRV) for fresh air supply and removal of excess moisture during the heating season; energy efficient lighting and bulbs; and low-volatile organic compound (VOC) paints, adhesives and sealants. Air filters for the HRVs and heat pump were MERV 8. All floors were equipped with carbon monoxide (CO) detectors. Central heating, ventilation and air conditioning (HVAC) systems equipped with additional dehumidification to control indoor moisture were installed in each apartment, with a basic continuous outdoor air ventilation. Operable windows also gave inhabitants some control over TC and IAQ.

The study utilised both subjective and objective assessment methods, including questionnaire surveys, field observations, and physical measurement of IEQ and was conducted in the

FIGURE 1. Apartment elevation.

fall of 2016. The methodology was first piloted on one house in the winter of 2016 to validate it, with the piloting resulting in modifying sections of the protocol presented in subsection 3.2. The pilot as well as the full study were reviewed and approved by the University of Manitoba Research Ethics Review Board.

3.2 Data collection

Snapshot measurements of temperature (i.e. air and radiant), air velocity, relative humidity (RH), carbon dioxide (CO_2), carbon monoxide (CO), total volatile organic compounds (TVOC), and particulate matter ($PM_{2.5\ \&\ 10}$) were conducted using electronic instruments in each apartment every minute over a 15-min sampling period. Further, radon, illuminance, background noise (BN) and apparent transmission loss (ATL) were also measured as shown in Table 1. The protocol used to conduct these measurements was based on a comprehensive review of existing IEQ protocols in the literature (e.g. Hui, Li, & Zheng, 2006; Zhao, Chen, Guo, Peng, & Zhao, 2004) and standards (e.g. American Society for Testing and Materials, 2014; Hong Kong Building Environmental Assessement Method Society, 2004; U.S. Green Building Council, 2013). The parameters of BN and ATL were measured according to ASTM E1574-98.

These measurements were conducted in the living and dining area (i.e. living room) of each apartment and in two bedrooms (i.e. bedroom 1 and bedroom 2) of different sizes and in opposite locations as shown in Figure 2. Since the study involved monitoring three out of a total of four spaces in each apartment, these measurements were considered representative of every apartment as explained further in Lai, Mui, Wong, & Law (2009). Due to the small size of the combined living room, dining area, and kitchen, the sampled data in the living and dining area was deemed representative of the kitchen environment. All instruments used in this study were factory calibrated. The instrumental setups for IAQ and TC were placed in the middle of each room at a height of 1.2 m and 1.1 to 1.5 m, respectively. Thermal comfort measurement involved profiling occupants at the feet, seated and standing levels. Radon was sampled every hour for 24 hours to provide more reliable results (Xie, Liao, & Kearfott, 2015). Lighting measurements in the living room were based on two sampling positions at a distance of 1 m from both windows, while in the bedrooms the measurements were conducted in the middle of the room given their small size. In evaluating the sound transmission properties of the interior wall partitions, radiating pink noise at a sound power level of 80 dB for each octave band was selected to represent the worst-case scenario of a loud party inside any of the bedrooms. BN was measured for a two-minute period after controlling all noise sources as much as possible.

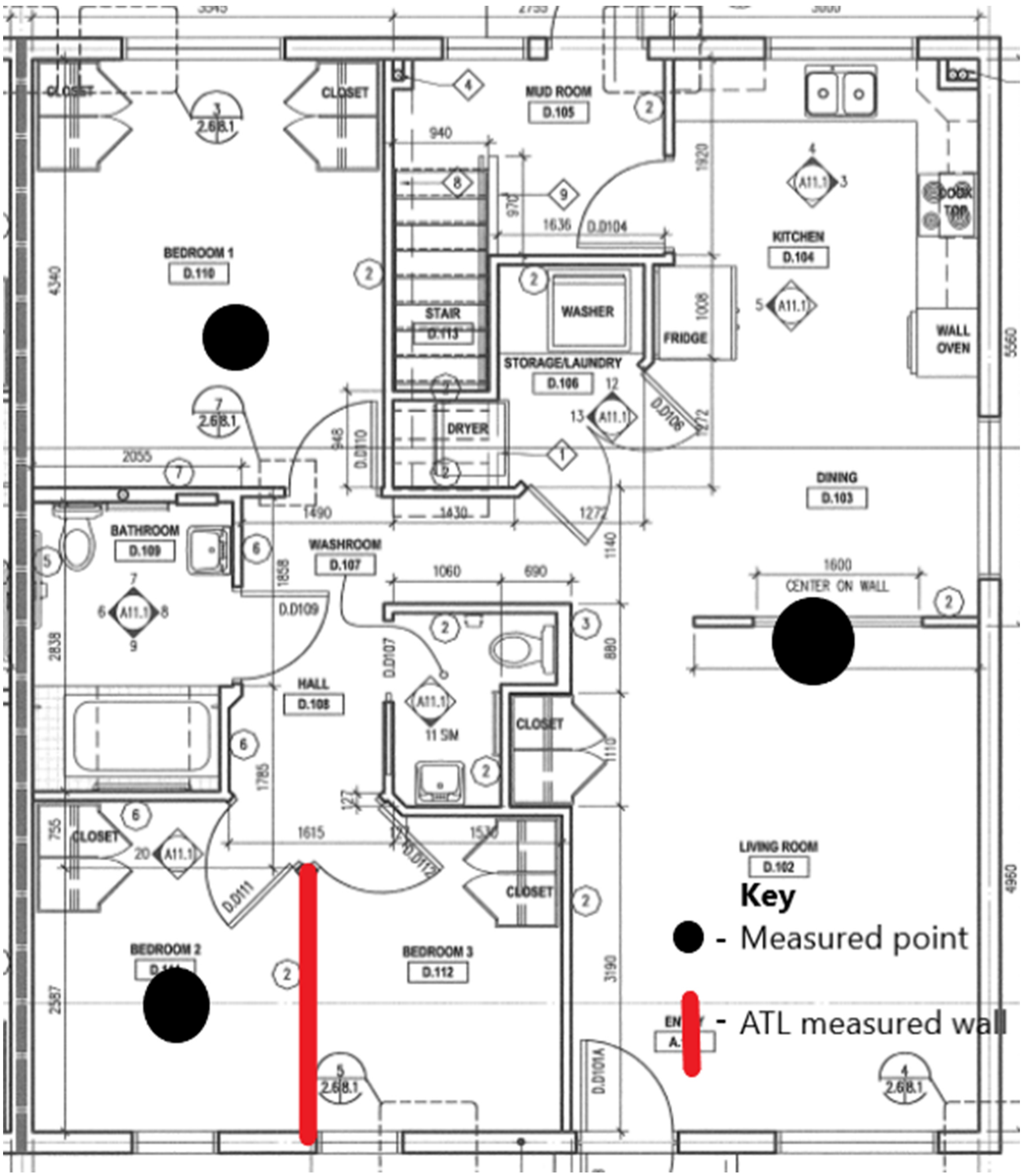
During the sampling period, occupants completed a questionnaire survey enquiring about their occupancy patterns (i.e. number of occupants, time spent indoors and activities), and their satisfaction with IEQ (i.e. adaptive control behaviours, IEQ problems, snapshot and long-term satisfaction with IEQ). Table 2 shows the specific variables the survey enquired about and the range of responses provided to occupants to rate each. The term "snapshot satisfaction" referred to their satisfaction with environmental parameters at the time of the IEQ physical measurements, while "long term satisfaction" went beyond the physical measurements to enquire about their satisfaction with IEQ in general over a longer time period. Occupants rated their temporary satisfaction on a 5-point Likert scale (i.e. 1—very uncomfortable/very dissatisfied to 5—very comfortable/very satisfied), which was subsequently converted into an artificial dichotomous variable (i.e. 1—uncomfortable/dissatisfied for ratings of 1 or 2, or 2—comfortable/satisfied for ratings of 4 and 5). Long-term satisfaction on the other hand, was rated using a 7-point Likert scale (i.e. 1—very dissatisfied to 7—very satisfied). Only adult occupants 18

TABLE 1. Summary of measurement protocol.

Parameter	Location	Unit	Instrument	Accuracy
Thermal Comfort				
Air Temperature	Bedrooms, Living room	Degree Celsius (°C)	Campbell Scientific 109-L	±6 °C
Radiant Temperature	Bedrooms, Living room	Degree Celsius (°C)	Campbell Scientific black globe L	±2% for 0 to 70 °C
Relative Humidity	Bedrooms, Living room	Percentage (%)	GrayWolf IQ 610	±3% for RH > 80%
Air Velocity	Bedrooms, Living room	Meters per second (m/s)	GrayWolf AS-201	±2%
Air Quality				
Carbon Dioxide (CO_2) & Carbon Monoxide (CO), Total volatile organic compound (TVOC)	Bedrooms, Living room	Microgram per cubic meter ($\mu g/m^3$)	GrayWolf IQ-610	±3% of meter reading
PM_{10} and $PM_{2.5}$	Bedrooms, Living room	Microgram per cubic meter ($\mu g/m^3$)	GrayWolf PC-3016A	
Radon	Basement	Bq/m^3	Sun nuclear	
Acoustic Quality				
Background noise	Bedrooms, Living room	Decibels (dB)	831 class 1 sound level meter	
Apparent Transmission Loss (ATL)	Bedrooms, Living room	Decibels (dB)	BAS001 speaker, BAS002 amplifier, and 831 class 1 sound level meter	
Lighting Quality				
illuminance level	Bedrooms, Living room	Lux	Delta Ohm LP PHOT 01	

years or older took part in the survey, resulting in a total of 27 occupants completing it, with at least one occupant from each apartment. The average number of occupants per household was six persons, with a standard deviation of 1.53 which is consistent with the design intent of heavy occupant density. A significant proportion of the occupants (i.e. 74.1%) had lived in their apartments for more than a year, indicating they had a fair knowledge of their indoor environment. Also, the majority (i.e. 85.1%) spent between 5 to 15 hours per day indoors

FIGURE 2. Sampling positions.



(i.e. at home), implying that occupants were likely to have considerable interaction with their indoor environment.

While the survey was being administered, visual inspection of the apartments was conducted using a physical observation sheet developed for this study. This inspection recorded the potential sources of indoor and outdoor pollution, outdoor temperature and sky conditions,

TABLE 2. Variables investigated in survey and responses available for each.

Variable	Potential Responses
Background	
Age	30 or under; 31–50; Over 50
Length of stay	< 1 year; 1–2 years; 3–5 years; > 5 years
Occupancy	
Rental choice	Comfortable indoor environment; Low energy consumption; Affordability of price or rent; Location in the city; Other environmental factors
Number of occupants	Open answer
Average time spent indoors (hours)	< 5; 5–10; 10-15; 15–20; > 20
Smoking indoors	Yes; No
Pet keeping	Yes; No
IEQ	
Indoor thermal environment snapshot satisfaction	Very uncomfortable; Uncomfortable; Neutral; Comfortable; Very comfortable
Indoor thermal environment problems (Hot temperature; cold temperature; damp air; dry air; drafts)	Always; Often; Sometimes; Rarely; Never
Thermostat or fan controls	Yes (very); Yes (quite); No; Don't know
Indoor thermal environment long term satisfaction	Very dissatisfied; Slightly dissatisfied; Dissatisfied; Neutral; Satisfied; Slightly satisfied; Very satisfied
Radon	Yes; No; Not sure
Mold	Yes; No; Not sure
Indoor air quality snapshot satisfaction	Very dissatisfied; Dissatisfied; Neutral; Satisfied; Very satisfied
Indoor air quality problems (stuffy/stale air; unclean/dusty air; garbage smell; cigarette smoke; sewer odor)	Always; Often; Sometimes; Rarely; Never
Indoor air quality long term satisfaction	Very dissatisfied; Slightly dissatisfied; Dissatisfied; Neutral; Satisfied; Slightly satisfied; Very satisfied
Indoor lighting environment snapshot satisfaction (natural and artificial)	Very dissatisfied; Dissatisfied; Neutral; Satisfied; Very satisfied
Indoor lighting long term satisfaction	Very dissatisfied; Slightly dissatisfied; Dissatisfied; Neutral; Satisfied; Slightly satisfied; Very satisfied
Speech privacy	Very dissatisfied; Slightly dissatisfied; Dissatisfied; Neutral; Satisfied; Slightly satisfied; Very satisfied

(continues)

TABLE 2. Variables investigated in survey and responses available for each. *(Cont.)*

Variable	Potential Responses
Noise level	No noise; Slightly noisy; Noisy; Very noisy; Limited tolerance
Sources of noise (Street; People; Animals; Neighbours; HVAC; Plumbing; Home appliances and electronics; Speech; Non-speech	Always; Often; Sometimes; Rarely; Never
Indoor acoustic long-term satisfaction	Very dissatisfied; Slightly dissatisfied; Dissatisfied; Neutral; Satisfied; Slightly satisfied; Very satisfied

visible air leaks, and the use of ventilation controls, including the set-points of the thermostat and HRV.

3.3 Data analysis

The collected data was analyzed using Statistical Package for the Social Sciences version 23.0. Descriptive statistics (e.g. mean, standard deviation) were calculated for the various environmental parameters measured. The Shapiro-Wilk test for normality was used to test the normality assumptions of the continuous data (i.e., objective measurements) and visual inspection of box-plots and qualitative assessment were used to identify outliers, particularly in the objective measurements. Values higher than the upper quartile plus three times the interquartile range were deemed outliers. However, outliers identified in the continuous data were subsequently retained in the dataset for reasons identified in the observation sheet.

Cronbach's alpha coefficient was used to test the reliability and internal consistency of the survey responses. The underlying objective of the reliability test was to determine whether the items of TC, IAQ, lighting, and acoustic quality scales respectively measured the same underlying dimension. The alpha values for TC, IAQ, lighting quality and acoustic quality were 0.617, 0.690, 0.753 and 0.814, respectively. Within the IEQ literature, the acceptable value of alpha ranges from 0.60 to 0.95 (Xue, Mak, & Cheung, 2014). In this study, all of the coefficients were above 0.60 indicating a good reliability of the scales.

Pearson correlation coefficient (r) was calculated to identify any relationships among the measured environmental parameters, while Spearman rank coefficient was calculated to investigate the relationship between snapshot and long-term IEQ satisfaction because the subjective dataset was assumed to not follow a normal distribution pattern.

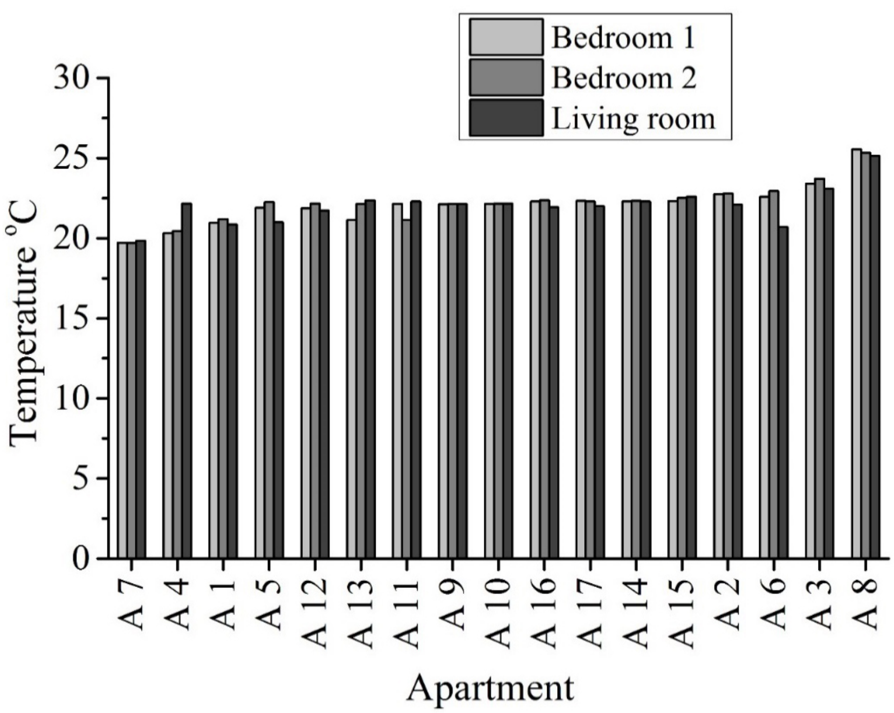
A one-way Analysis of Variance (ANOVA) test was used to test the difference between the mean sound levels of the three sampled spaces (i.e. bedroom 1, bedroom 2 and living room) in the measured apartments because of the different possible sources of noise. This test was considered appropriate because of the equal sample size of the groups; and in particular because the sound level data was assumed to follow a normal distribution (Laerd Statistics, 2015). Subsequently, a Tukey-Kramer post hoc test was run to test the differences among the specific groups in all possible pairwise comparisons (Gauthier, 2016). Statistical significance was defined as ($\rho < .05$). Box plots were constructed showing the magnitude and variability of the environmental parameters experienced by the snapshot satisfied versus snapshot dissatisfied occupant groups. The differences between these two groups were examined using the Mann-Whitney U-test.

4. RESULTS AND DISCUSSION

4.1 Thermal comfort

The measured air velocities in the three sampling spaces in the 17 apartments were within the range of 0.00 to 0.09 m/s. It was therefore not surprising that the majority of the apartments had portable fans to improve air movement and thus TC within the apartment. Figure 3 shows that the mean values of the indoor air temperature profile (i.e. feet level, chest level, head level) measured for a seated occupant in bedrooms 1 and 2 and the living rooms in all apartments ranged between 19.0 and 26.0 °C. Correspondingly, the indoor radiant temperature in the same locations ranged between 20.0 and 26.0 °C. Outside temperature ranged from 8 to 20 °C during the sampling period. These results were similar to the ones by Langer et al. (2015) on green residential buildings in Sweden, the one by Xiong et al. (2015) on LEED gold and platinum apartments in northeastern United States, and other studies on social housing in the United Kingdom (McGill et al., 2015) and other regions of Europe (see Kolokotsa & Santamouris, 2015). Also, indoor air temperatures appeared to have no statistically significant relationship with outdoor temperatures, despite the negative associations between them. The air temperature in all apartments were within the recommended levels of comfort (i.e. 18.0–24.0 °C) defined by McGill et al. (2015), except for the mean air temperatures in apartment eight (A8) (i.e. 25.3 °C), even though outside air temperature at that time was only 15 °C. This suggests the use of

FIGURE 3. Distribution of mean air temperature values per apartment and space.

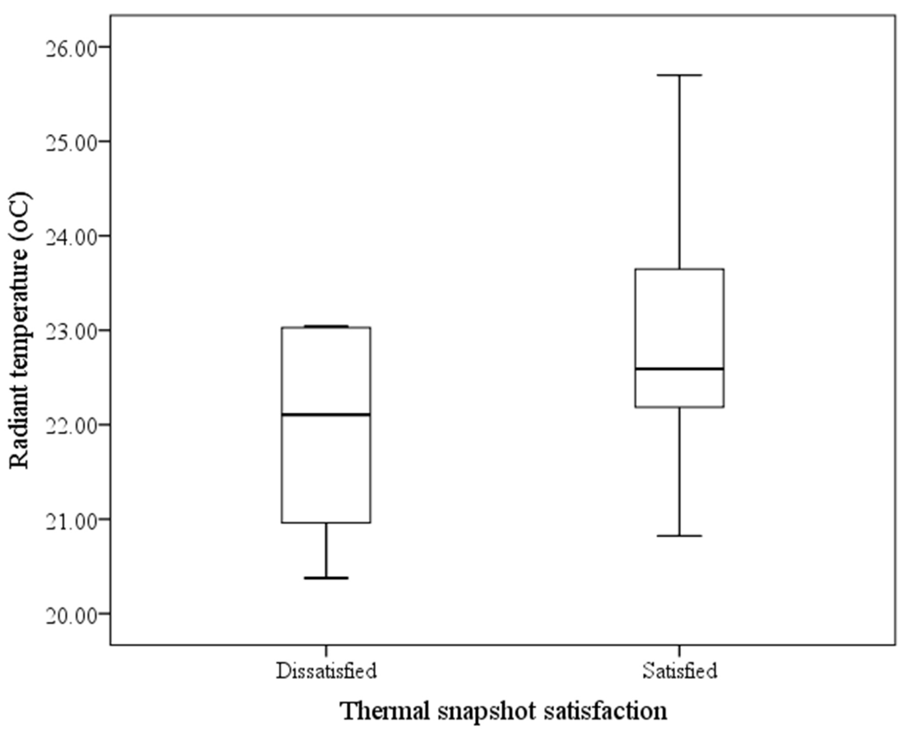


mechanical heating in that apartment as evidenced by the thermostat reading of 26°C at that time. Interestingly, this apartment's occupants were satisfied with snapshot TC. This could be due to them being originally from a hot-climate country and as such used to relatively higher indoor temperatures.

The RH values in bedrooms 1 ranged from 33.0 to 62.0%, with a mean of 45.0%. Additionally, those of bedrooms 2 and the living rooms ranged from 30.0 to 59.0% and 37.0 to 63.0%, respectively, with corresponding mean values of 43.0% and 48.0%. Although some of the locations in the apartments exceeded slightly the recommended levels of 30.0% to 60.0% set by (McGill et al., 2015), the mean levels reported in this study were within recommended levels.

Because results from the objective measurements alone or subjective survey responses alone can be one-sided and thus misleading, the objective measurements of radiant temperature, air velocity and RH were distributed over the snapshot satisfied and snapshot dissatisfied groups of occupants. The distributions of radiant temperature per occupant group is presented in Figure 4. The Mann-Whitney U-test run to assess differences in these parameters between the satisfied and dissatisfied groups found no statistically significant differences. The mean and median values of air velocity were 0.01 m/s and 0.003 m/s for the satisfied group, respectively, and were 0.002 m/s and 0.001 m/s for the dissatisfied group, respectively. While these levels were too small to have any significant impact on thermal snapshot satisfaction, occupants in the dissatisfied group experienced relatively higher air velocity which may explain their dissatisfaction. Occupants' thermal snapshot satisfaction appeared not to corroborate the physical measurement results given that only 63.0% of the occupants rated their snapshot satisfaction as comfortable, failing thus the 80% occupants' satisfaction benchmark set by the American Society for

FIGURE 4. Distribution of radiant temperature values per TC snapshot satisfaction occupant group.



Heating Refrigerating and Air Conditioning Engineers (2013) for acceptable indoor thermal environment. A larger sample of survey respondents may be needed to validate these results.

4.2 Indoor air quality

Occupants' long-term IAQ satisfaction in the studied houses was below the American Society for Heating Refrigerating and Air Conditioning Engineers (2013) threshold of 80%. Approximately 67.8% of the occupants were satisfied with it, whereas 84.6% were satisfied with snapshot IAQ. The spearman rank correlation analysis found a moderate statistically significant positive correlation ($r = 0.552$, $\rho = 0.005$) between occupants' snapshot and long term IAQ satisfaction. Visual inspection of the box plots for PM_{10}, TVOC, CO and CO_2 with respect to the IAQ snapshot satisfaction groups showed that occupants in the dissatisfied group were in general exposed to higher concentrations of these pollutants than those in the dissatisfied group, a trend consistent with that in a study by Du et al. (2015).

4.2.1 PM_{10} and $PM_{2.5}$

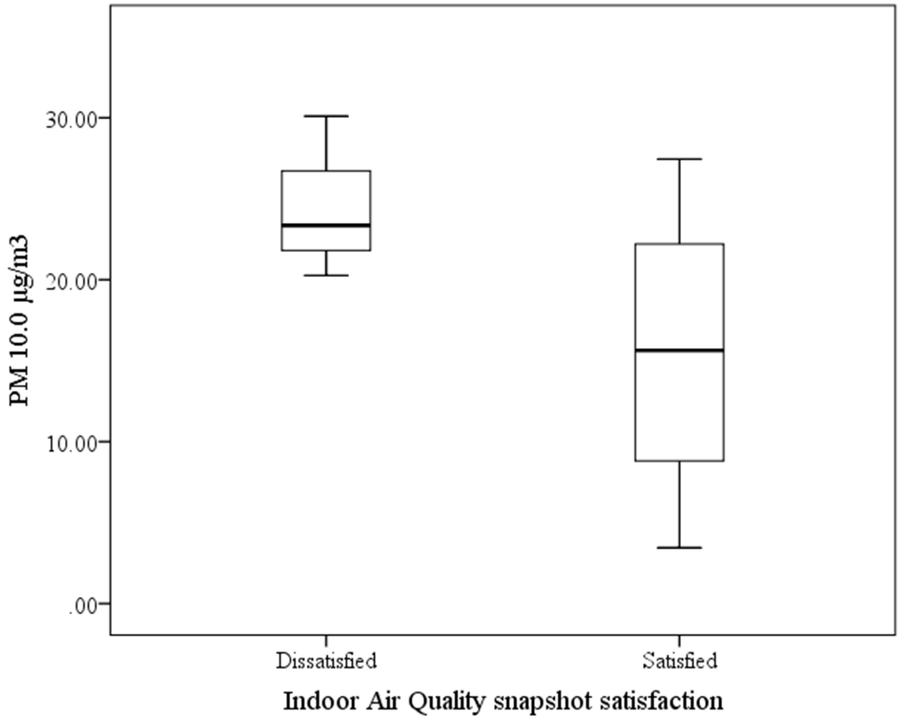
The mean levels of PM_{10} in bedrooms 1, 2 and the living rooms were 21.32 $\mu g/m^3$, 17.50 $\mu g/m^3$ and 18.64 $\mu g/m^3$, respectively. These mean levels were within the threshold of 50 $\mu g/m^3$ (Du et al., 2015) whereas the maximum levels in bedrooms 1 (i.e. 86.37 $\mu g/m^3$) and 2 (i.e. 56.18 $\mu g/m^3$) exceeded that threshold. Similarly, mean $PM_{2.5}$ levels in bedrooms 1, 2 and the living rooms were 4.784 $\mu g/m^3$, 5.634 $\mu g/m^3$, and 6.231 $\mu g/m^3$, respectively and were also within the recommended threshold of 25 $\mu g/m^3$ set by (Du et al., 2015). Nevertheless, unlike PM_{10}, the maximum levels of $PM_{2.5}$ in bedrooms 1 (i.e. 12.321 $\mu g/m^3$), 2 (i.e. 16.272 $\mu g/m^3$) and the living rooms (i.e. 23.146 $\mu g/m^3$) did not exceed that threshold. Differences in PM_{10} levels observed between spaces of the same apartment were marginally lower than differences observed between the different apartments. The larger differences in PM_{10} levels between apartments could be due to the socio-economic differences found between them and that relate to aspects such as occupant density and occupant behaviour. They could also be due to differences in the operation of these apartments' ventilation systems. For example, the ventilation system in apartment A6 was turned off because it was vacant during the monitoring period, which may explain the high PM_{10} (i.e. 86.37 $\mu g/m^3$) levels found in this apartment. Potentially high outdoor PM levels may also explain the high indoor PM levels and be a predictor of them as suggested by (Coombs et al., 2016); (Burgos, Ruiz, & Koifman, 2013; Ni et al., 2016); however, these outdoor levels were not measured in this study.

Figure 5 shows the distribution of PM_{10} levels by IAQ snapshot satisfaction group of occupants. PM_{10} levels were found to be higher in the apartments of the dissatisfied group (mean = 24.57 $\mu g/m^3$; median= 23.35 $\mu g/m^3$) than in those of the satisfied group (mean = 14.76 $\mu g/m^3$; median = 15.63 $\mu g/m^3$). Conversely, $PM_{2.5}$ levels were slightly lower in the apartments of the dissatisfied group. The Mann-Whitney U-test only found a statistically significant difference in the mean PM_{10} level between the two groups at 9.81 (95% CI, 1.09 to 18.54), $t(20) = 2.46$, $p = 0.029$, $d = 1.46$. Furthermore, a moderate statistically significant negative association ($r = -0.471$, $\rho = 0.027$) was found between occupants' IAQ snapshot satisfaction and PM_{10} levels only, suggesting PM_{10} may be a better indicator of that satisfaction than $PM_{2.5}$.

4.2.2 CO and CO_2

Mean CO levels in bedrooms 1, 2 and the living rooms were 0.97 ppm, 0.92 and 1.03 ppm, respectively. These CO levels were comparable to the levels found in other studies in literature

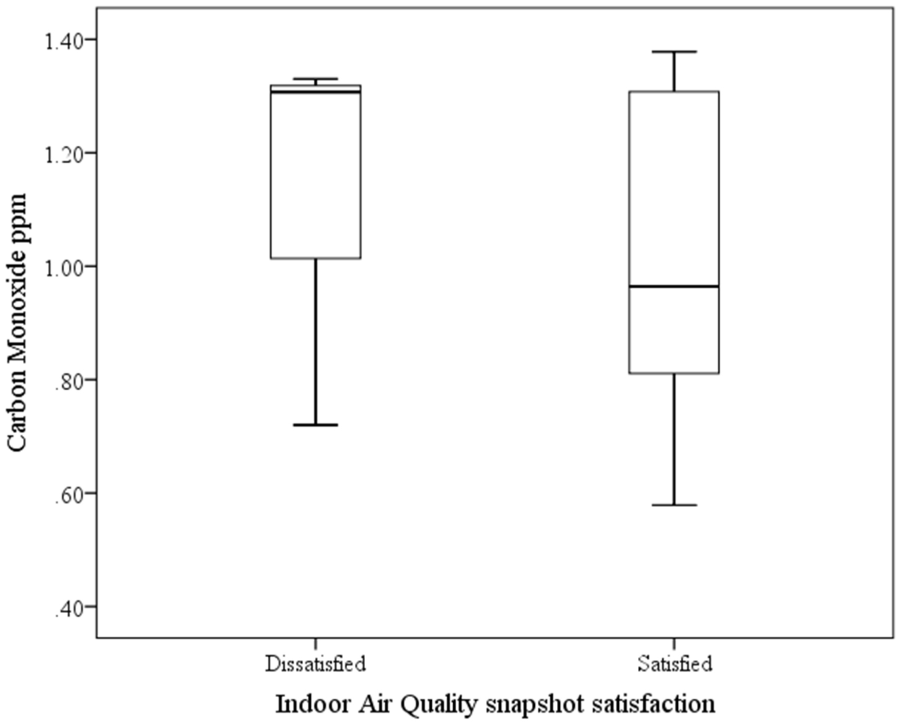
FIGURE 5. Distribution of PM_{10} values per IAQ snapshot satisfaction occupant group.



(Y. Xiong et al., 2015) and below the 24-h recommended threshold of 25 ppm (or 9 ppm for 8 hours) defined by (Health Canada, 2016). This was not surprising given that there were no obvious possible indoor sources of CO. High CO levels are usually attributed to indoor smoking (Q. Li, You, Chen, & Yang, 2013). To explore this relationship, the measured apartments were further categorized into smoking and non-smoking houses based on whether the occupants smoked indoors or not. Surprisingly, the median CO levels were 0.84 ppm and 1.02 ppm in smoking and non-smoking houses respectively, indicating that indoor smoking may not be the leading source of CO in these houses. Although this was not investigated further, indoor CO levels may have been due to outdoor sources such as automobile exhausts from traffic in nearby roads and railways. Figure 6 shows the distribution of CO by IAQ snapshot satisfaction group. The results indicate that CO levels were higher in the apartments of the dissatisfied group (mean = 1.12 ppm; median=1.31 ppm) than in those of the satisfied group (mean = 1.01 ppm; median = 0.96 ppm) although the difference between the groups was not statistically significant.

CO_2 levels varied between 533.54 ppm and 1409.11 ppm during the monitoring period, and were closer to the levels reported by Noris et al. (2013) in California, but higher than the levels reported by Xiong et al. (2015) in northeastern USA. Nevertheless, the results in these studies were based on long term measurements of CO_2. Moreover the study by (Noris et al., 2013) took place in the summer and winter seasons. Mean CO_2 levels in the living rooms (i.e. 748.29 ppm), bedrooms 1 (i.e. 873.26 ppm) and 2 (i.e. 910.70 ppm) were well within the threshold of 1000 ppm (Du et al., 2015; Noris et al., 2013). Interestingly, the living rooms' mean CO_2 level (i.e. 748.29 ppm) were lower than the mean levels in the other two bedrooms (i.e. 873.26 ppm for bedrooms 1 and 910.70 ppm for bedrooms 2) despite people spending

FIGURE 6. Distribution of CO values per IAQ snapshot satisfaction occupant group.

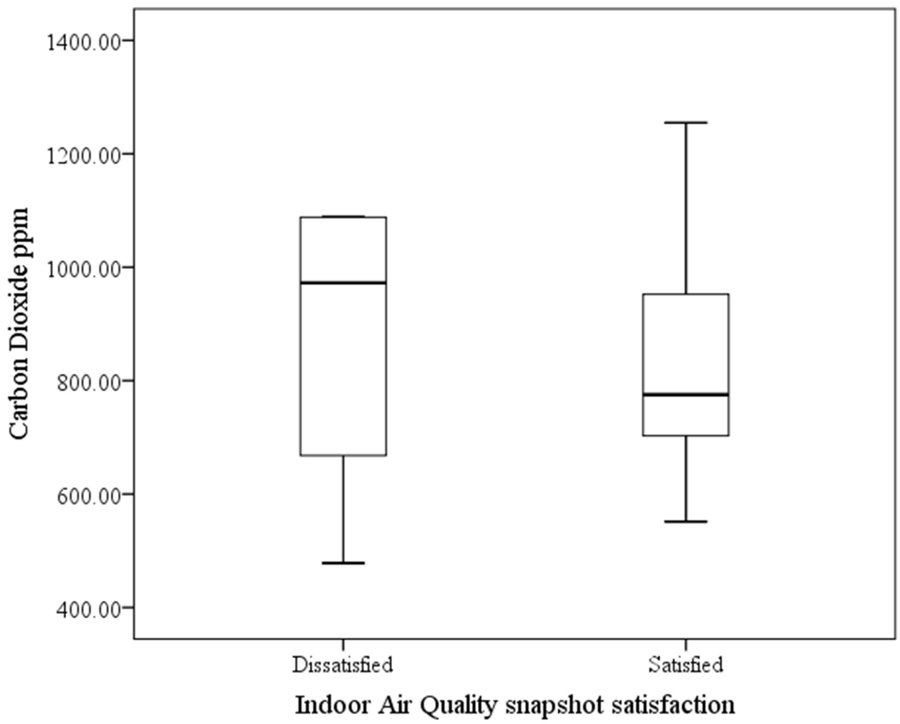


more time in their living rooms than in the two bedrooms. The lower level in the living rooms could have been due to their large size relative to the bedrooms, to the frequent opening of living room windows and to the use of HRV to displace indoor air with outdoor air. Figure 7 shows the distribution of CO_2 level by IAQ snapshot satisfaction group. CO_2 levels were higher in the apartments of the dissatisfied group (mean = 877.98 ppm; median = 972.37) than in those of the satisfied group (mean = 812.73 ppm; median = 775.41 ppm) although the difference was not statistically significant. These results confirm the findings of (Du et al., 2015).

4.2.3 Total volatile organic compounds (TVOC)

TVOC levels in the studied apartments ranged from 536.29 $\mu g/m^3$ to 3,955. 93 $\mu g/m^3$. The mean levels in bedrooms 1, bedrooms 2 and the living rooms were 972.84 $\mu g/m^3$, 888.26 $\mu g/m^3$ and 1070.52 $\mu g/m^3$, respectively. TVOC levels in most apartments were below 1000 $\mu g/m^3$. The highest levels were recorded in apartment A10 and ranged from 2,400.00 $\mu g/m^3$ to 3,955.93 $\mu g/m^3$. These levels were higher than the median level of 270.00 $\mu g/m^3$ reported by a similar study by Langer et al. (2015) on green residential housing in Sweden. Although the levels were still within the Health Canada (2016) recommended benchmark of 200 to 30,000 $\mu g/m^3$ for a 15-min sampling time, the differences in TVOC levels between the measured apartments were not expected to be large. This is because the houses were constructed using the same materials and had been in operation for the same number of years. Outdoor levels were not measured making it difficult to ascribe the peak indoor levels in apartment A10 to them. Moreover, had outdoor TVOC levels been high, they would have led to higher indoor TVOC levels in several houses and not just A10. This high indoor level could therefore be due to the

FIGURE 7. Distribution of CO_2 values per IAQ snapshot satisfaction occupant group.

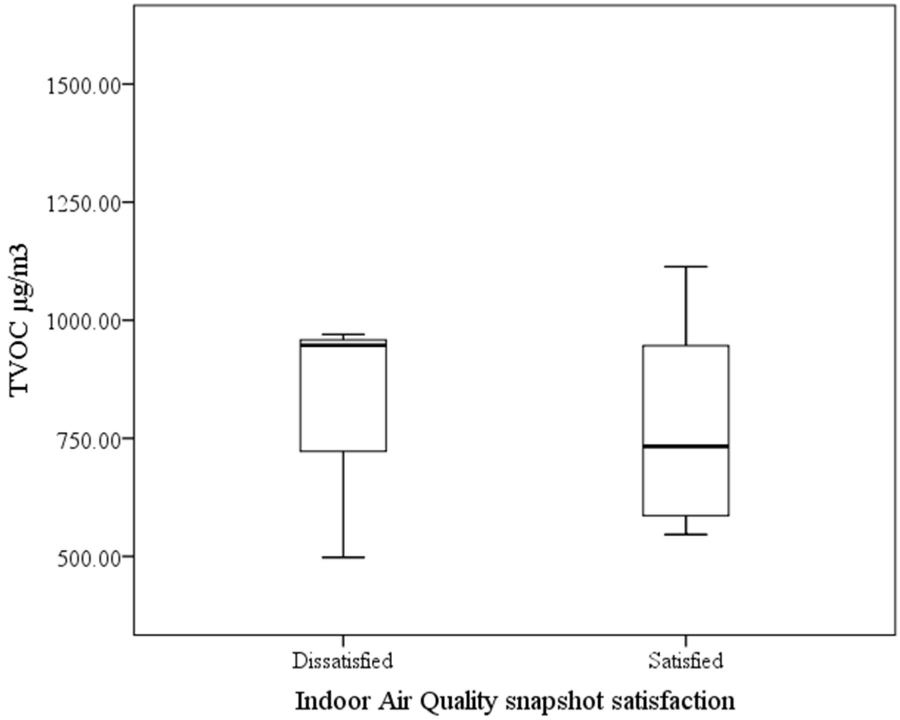


use of indoor sources such as household and consumer products (e.g. nail polish, fragrance and cleaning agents) with high emission rates or to inadequate local ventilation (Hormigos-Jimenez, Padilla-Marcos, Meiss, Gonzalez-Lezcano, & Feijó-Muñoz, 2017) in this specific apartment. But given that CO_2 levels, a major determinant of ventilation adequacy, were within acceptable limits in that apartment, indoor sources alone may explain this apartment's elevated TVOC levels. As shown in Figure 8, TVOC levels in the apartments of the IAQ snapshot satisfied group (mean = 737. 15 $\mu g/m^3$; median = 631.64 $\mu g/m^3$) was lower than in those of the dissatisfied group (mean = 803.75 $\mu g/m^3$; median= 790.81 $\mu g/m^3$) although the difference was not statistically significant.

4.2.4 Radon

As can be seen in Figure 9, the mean radon levels in A1, A2, A3, A5, and A10 were 163.9, 30.9, 66.5, 37.8 and 31.4 bq/m^3 respectively. Only apartment A1 was found to have a slightly higher mean radon level than the reference exposure level of 148.0 bq/m^3 set by the New York State department of environmental conservation (2017). However, Health Canada (2014) indicates no remediation action is required for radon levels less than 200.0 bq/m^3. Given that the major source of radon is infiltration from the soil, it's not clear why those differences in radon levels exist between the different apartments. This is because the houses are exposed to the same soil and weather conditions and use the same passive ventilation strategies. They are also of the same age, were built by the same contractor using the same methods; therefore, one house is unlikely to have considerably more cracks than others. Although physical observation of the measured

FIGURE 8. Distribution of TVOC values per IAQ snapshot satisfaction group.

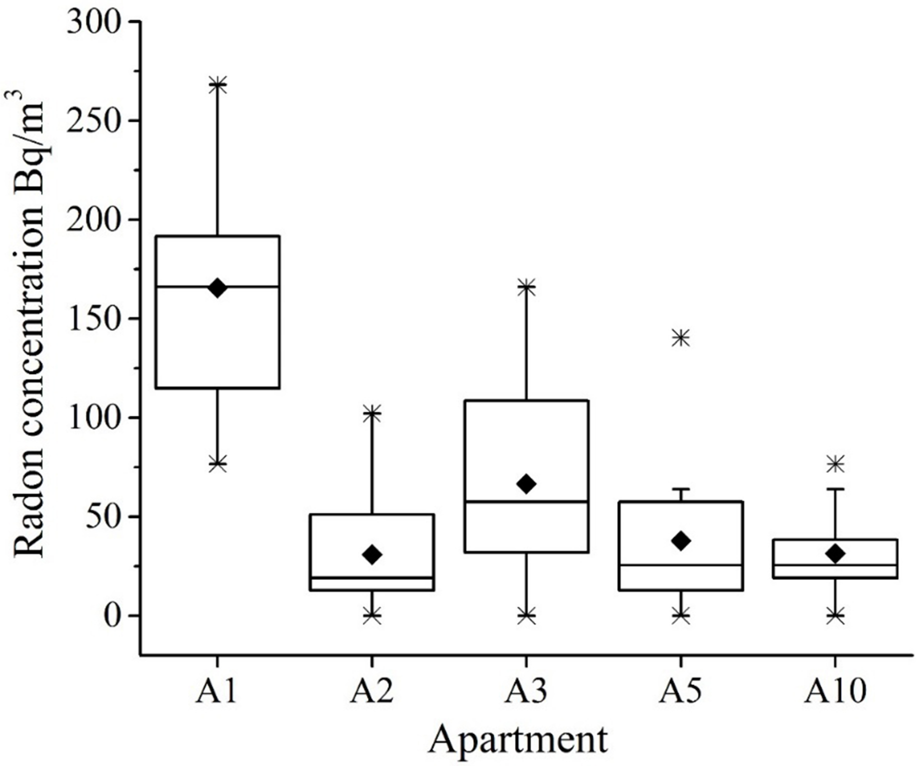


apartments revealed no visible cracks in the basement, invisible cracks may explain the higher radon levels in apartment A1. Other environmental parameters (e.g. indoor relative humidity, indoor-outdoor temperature difference) may have also contributed to those higher radon levels; however, none of them were measured in the basement.

4.3 Lighting

There were large differences in electric and daylight illuminance levels between the different apartments but small differences in these levels between the different spaces in the same apartment which is consistent with a previous study by Li et al. (2006). Mean daylight illuminance levels ranged between 12.32 lx and 1,038.00 lx. These differences in daylight illuminance levels between apartments may be due to the time of day, prevailing weather conditions (i.e. overcast, foggy, cloudy), the orientation of the building, and the type of shading used. Further, apartments with blinds only appeared to have increased daylight illuminance levels than apartment combining curtains and blinds. Similarly, spaces with no internal shading seemed to have higher daylight illuminance levels than those with internal shading (i.e. blinds or curtains). Not surprisingly, outdoor weather conditions appeared to have a direct impact on daylight illuminance levels indoors. For instance, the weather was foggy and partly cloudy when conducting the physical measurements in apartment A14, which may explain its low mean daylight values in the living room (i.e. 12.32 lx), bedroom 1 (i.e. 98.6 lx) and bedroom 2 (i.e. 14.21 lx). These results were in general similar to the few IEQ studies that have reported on lighting in the literature (D. H. W. Li, Wong, Tsang, & Cheung, 2006; Q. Li et al., 2013).

FIGURE 9. Distribution of radon values per apartment.



The distribution of daylight illuminance level per daylight snapshot satisfaction group of occupants is showed in Figure 10. Occupants that were satisfied with indoor daylight received slighter higher illuminance levels (mean = 169.27 lx; median= 39.03 lx) than those who were dissatisfied with it (mean = 130.31 lx; median = 54.34 lx). The mean illuminance level for the satisfied group was slightly above the threshold level of 150 lx recommended by Li et al. (2016).

4.4 Acoustics

In residential buildings, noise levels above 70 dB(A) usually cause discomfort and make people sick (Neitzel, Heikkinen, Williams, Viet, & Dellarco, 2015). In this study, the majority of the measured BN levels were below 50 dB(A). In fact, measured A-weighted BN levels varied between 27.7 and 75.3 dB(A). Interestingly, the living rooms in all apartments recorded slightly higher BN levels than the two bedrooms. This could be due to the living rooms being closer than the bedrooms to the additional noise generated by refrigerators and nearby traffic noise. A one-way ANOVA test showed statistically significant differences in the means of background noise levels across the different spaces (living room, bedroom 1 and bedroom 2) of the same apartment, $F(2, 47) = 10.572$, $p < .0002$. The Tukey-Kramer Post Hoc test revealed that these differences in means were statistically significant only between the living room (i.e. 47.39 dB(A)) and each of the two bedrooms (37.22 dB(A) for bedroom 1 and 37.32 dB(A) for bedroom 2).

Figure 11 shows that occupants who were satisfied with snapshot acoustics experienced A-weighted BN levels (mean = 42.20 dB; median = 42.20 dB) slightly above that of the

FIGURE 10. Distribution of daylight illuminance levels per lighting snapshot satisfaction group.

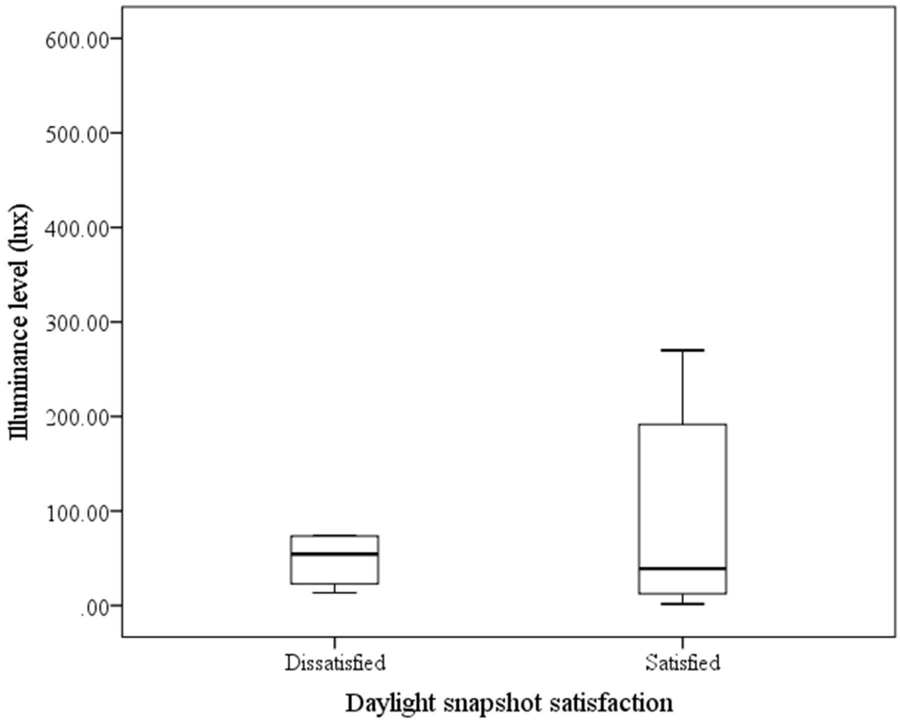
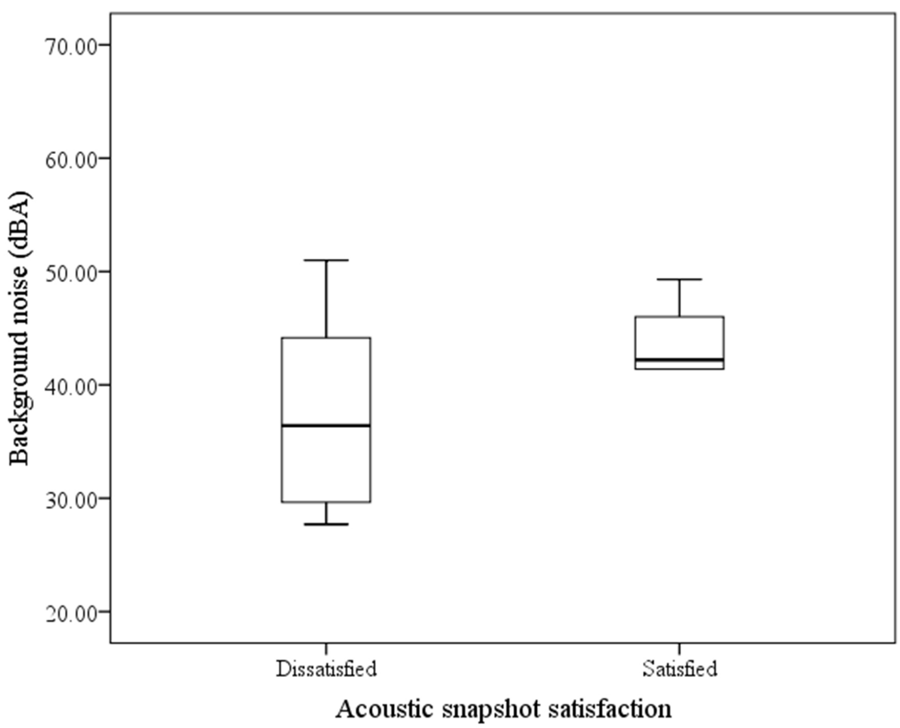


FIGURE 11. Distribution of A-weighted background noise values per acoustic snapshot satisfaction group.

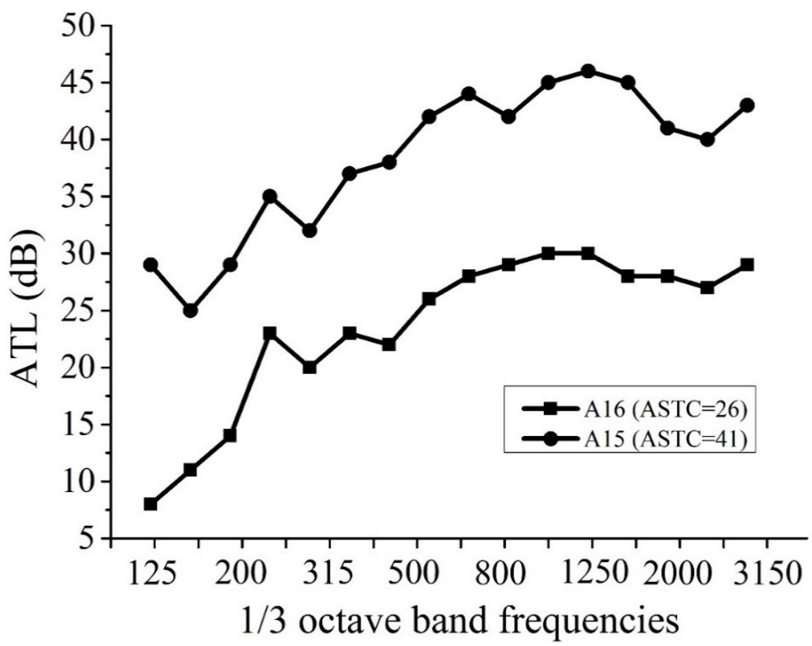


dissatisfied group (mean = 38.63 dB; median = 36.40 dB). This indicates that occupants' subjective judgment may have been largely influenced by sources other than background noise. With respect to indoor noise sources, occupants acknowledged that the majority of background noise came from outside the house. They found the most frequent indoor noise sources to be home appliances, electronics (e.g., TV sets, game consoles), and non-speech sound (i.e. impact noise e.g. footsteps). Although most studies on green residential houses (Zalejska-Jonsson, 2012, 2014) found noise from ventilation systems and fans to be a major problem, this was not the case in this study. This could be due to the houses in this study being relatively small and thus likely to have small size ventilation systems that emit low noise levels.

4.4.1 Transmission Loss

The apparent sound transmission class (ASTC) of the partition wall between the bedrooms were determined to be between 26 and 41, with a sum of deficiencies less than 32. However, a significant proportion of the apartments were above ASTC 35, which meant that loud speech will be heard but not understood. Given the range of ASTC values measured, traffic noise and home music systems would still be a potential problem. Apartment 15 with highest ASTC (i.e. 41) and the one with the lowest ASTC (i.e. 26) were analyzed to further explore the 1/3 octave band filtered ATL. The results are presented in Figure 12. Even though these two apartments were adjacent to one another, significant differences in transmission loss were observed at every frequency. However, they all seemed to improve in performance at higher frequencies (i.e. above 1.5K hertz). This partly explains why human speech, which occur at higher frequencies, appeared not to be a major noise problem.

FIGURE 12. Sound transmission loss values of two extreme apartments.



5. CONCLUSIONS

This study aimed to investigate the IEQ performance of green low-income single family residential housing in Brandon, Manitoba, Canada. Unlike other studies on IEQ in residential buildings, this study combined both snapshot physical measurements of all four main IEQ factors (i.e. thermal, air quality, acoustic and light) and an occupant survey to evaluate occupants' satisfaction with these factors. This is to overcome the inherent problems associated with relying on only one type of measurement. The study provides empirical evidence about the post-occupancy performance of residential buildings that can help improve occupants' satisfaction with future social housing projects.

The results of the study revealed some discrepancies between the physical measurements of IEQ factors and occupants' satisfaction with these factors. For instance, 35% of respondents were uncomfortable with TC, even though TC parameters such as air temperature, radiant temperature and RH were well within recommended levels. This is in contrast with IAQ results where occupants experiencing lower levels of indoor air pollutants were in general more satisfied with IAQ. The results also showed that although TVOC levels were below recommended levels, elevated levels were recorded in one apartment, likely due to indoor furnishings and the frequent usage of cleaning agents and household products in it, thus the need to use low-VOC emitting finishes and products in the future. This reinforces the need to raise occupants' awareness of the impact of their activities on their environment, especial in low-income or social housing environments. Occupants reported noise from the outside as the most disturbing, probably because of the lack of control over these sources of noise and the inability of the walls to adequately attenuate noise (STC < 45) such as traffic noise. Occupants' acoustic snapshot satisfaction also appeared related to outdoor noise rather than background noise, thus the need to take into account outside-to-inside sound attenuation strategies by improving outdoor sound insulation to maintain privacy.

While a one size fits all approach to improving the IEQ quality of low-income households does not exist (Santamouris et al., 2007), occupants' feedback on IEQ can bring into attention solutions that practitioners never thought of. The findings of this study suggest that homes' indoor environments should be customised to their occupants' needs. These occupants tend to have frugal lifestyles and be cost-sensitive (e.g. Nahmens, Joukar, & Cantrell, 2015; Peretti, Pasut, Emmi, & De Carli, 2015; Soebarto & Bennetts, 2014). They are therefore willing to trade-off comfort for energy savings, which might reflect in their control of the indoor environment through strategies such as the opening of windows, the use of ceiling fans and clothing adjustments. Although the impact of these lifestyles or cost-sensitive strategies on IEQ was not apparent in this particular study partly because heating and cooling costs are subsidised by the government, they should be taken into consideration when designing buildings for low-income households. The results on TC for example showed that occupants of one apartment were accustomed to relatively high indoor temperatures, highlighting the need to offer occupants controls that would enable them to customise their indoor environment to their preferences. Thermostat set-points were also found to have an influence on indoor temperatures, thus the need for controls that are user-friendly. A consistent observation throughout most evaluated apartments was the availability of portable fans; the assumption being that occupants did not find fresh air supply sufficient. Future social housing should therefore incorporate at a minimum efficient ceiling fans to improve indoor comfort. This recommendation supports an earlier assertion by Santamouris et al. (2007) that oscillating fans can increase air speed and thus occupants' comfort. The high temperatures in one apartment may also be related to the inadequate use of ventilation controls, thus the need to provide occupants with adequate training on those controls when appropriate.

Future research should focus on analyzing a larger sample of social houses and apartments and survey a larger number of home occupants in order to validate and generalize the results of this research. This evaluation should also extend beyond Manitoba to include the rest of Canada and should extend beyond the fall season to include the whole year. This larger-scale evaluation may reveal different results; therefore, this study's results should be read with those limitations in mind.

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