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Application of Three Different Data Streams to Study Building Deficiencies, Indoor Air Quality, and Residents' Health

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Abstract

This pilot-level project investigated the potential to use, integrate, and correlate traditional indoor air quality investigation data and the use of questionnaires with spatially resolved infrared thermography imaging to investigate building deficiencies and their role in indoor air quality (IAQ) and residents' health in two residential multi-apartment buildings. Among the deficiencies detected by the 3D thermography, missing insulation correlated best with the IAQ measurement data and questionnaire data. Apartments missing more than 5% of insulation in their exterior wall ("high" group, n=6) had a significantly higher number concentration of ultrafine airborne particles (diameter < 300 nm) (p=0.013) and their indoor/outdoor ratio (p=0.029) compared to apartments where less than 5% of insulation was missing ("low" group, n =14), likely due to particle penetration from outdoors. The difference was driven by apartments with no combustion sources, e.g., smoking, burning of candles or incense. In apartments with the presence of such combustion sources, particles generated indoors overwhelmed the influx of ultrafine particles from outdoors. High levels of missing insulation ranging from 0.55% to 19.62% were detected in apartments with asthma attacks in the past 12 months. Asthma attacks were also associated with the presence of combustion sources indoors (p=0.027). Corner apartments had a higher fraction of missing insulation compared to non-corner apartments (p=0.002). Our data suggest that integration of different data streams is feasible that it could produce a more comprehensive IAQ investigation. This pilot-level study should be performed on a larger scale to examine its wider applicability in the IAQ field.

Keywords: Insulation, Indoor air quality, Ultrafine particles, Building deficiency, 3D thermography, Occupant behavior

Introduction

Over the past 20 years, studies have shown strong correlations between exposure to ambient particulate matter (PM) and a range of negative health effects, including early mortality (Klemm and Mason 2000; Schwartz et al. 1996; US EPA 2014; Wang et al. 2018a), exacerbation of respiratory tract disease, reduced lung function (Xu et al. 2018), and cardiovascular disease (Dabass et al. 2018; Dominici et al. 2006; Erqou et al. 2018). Every 10 $\mu g/m^3$ increase in $PM_{2.5}$ particle concentrations (particles <2.5 μm in diameter) results in a 6% to 18% increased risk of cardiopulmonary disease and increased all-cause mortality (Eftim et al. 2008; Pope et al. 2002, 2004); every 10 $\mu g/m^3$ increase in PM_{10} particle concentration (particles <10 μm in diameter) is associated with 0.2 % to 0.6% increase in all-cause mortality (Janssen et al. 2013; Samoli et al. 2008).

Negative health effects of air pollution are especially pronounced when high levels of outdoor pollution are combined with high levels of indoor pollutants, including $PM_{2.5}$, PM_{10}, NO_2, SO_X, O_3, and CO (Gouveia and Junger 2018; Mathieu-Nolf 2002; USEPA 2003). The concern over indoor exposures is amplified by the fact that people spend about 87% of their time indoors (Klepeis et al. 2001).

A variety of chemical and biological agents such as environmental tobacco smoke, pesticides, house dust, fungi, and allergens, can be present indoors and affect indoor air quality (IAQ), and, in turn, residents' health, including allergic reactions and asthma development and/or exacerbation. The indoor exposure levels to some of these contaminants are thought to have increased with the modernization of housing design, including higher indoor temperatures, extensive use of furnishings and carpeting, improved insulation and weatherization, and low ventilation rates (Ben-David and Waring 2018; Kaunelienė et al. 2016).

In addition, building design and features themselves might affect IAQ (Chenari et al. 2016; Niu 2004). However, so far there is inadequate understanding of the relationships between exposures to indoor pollutants, health symptoms, and buildings themselves, including their design, structural anomalies, and maintenance practices (Allacci 2005; Mendell et al. 2002). While improper design and maintenance of building HVAC systems are known to increase the risk of sick building syndrome (SBS), infections, asthma and allergies (Bernstein et al. 2008; Platts-Mills 1994; Wargocki et al. 2002), structural deficiencies and their relationship to negative health effects are less well understood. Dales et al. (2008) suggested that IAQ and its effect on human health in residential buildings were determined by both lifestyle choices (indoor smoking, pets, housekeeping) and building structure and quality. Building management including operation and maintenance, and practices are also important determinants of occupant health as they may contribute to IAQ problems (Bonnefoy et al. 2003; Oliver and Shackleton 1998; Weich et al. 2002).

Walkthroughs and visual inspections are commonly used to investigate building conditions and potential deficiencies; however, they are costly, time-consuming and, due to their reliance on visual inspection, might miss important building performance characteristics (Balaras and Argiriou 2002). Typical indoor air investigations rely on air sampling, monitoring, and analysis, which provide information about the quality air that the building occupants breathe, but such methods often are time-consuming and expensive. Structured questionnaires also are used in IAQ studies to obtain information regarding occupants' experiences with the building and its environment, including self-reported health status of household members (Dales et al. 2008; Hansen 1993; Meng et al. 2005; Lawrence and Khan 2018; Wang et al. 2016; Wang et al. 2018b; Wong and Huang 2004; Zhou et al. 2018). In recent years, there has been an increased use of infrared thermography (IRT), where the resulting 3D thermal profiles of buildings were used to investigate the state and performance of buildings. The development and application of 3D thermal profiles allow a non-destructive, minimally intrusive, accurate, and rapid detection of subsurface deficiencies caused by moisture intrusion and poor construction quality making this method superior to visual inspections (Kylili et al. 2014; Meola and Carlomagno 2004). A case study conducted by Ljungberg in 1996 explored the concept of using infrared thermography as an important diagnostic tool to detect sick building syndrome and overview any building related damages. An IRT study by Dall'O' et al. 2013 sampled 14 existing buildings located in Italy and determined the feasibility of applying this technique to evaluate the energy performance of the buildings. A recent study assessed the air leakage points in a multi-story residential building in Portugal using an IR camera; it also quantitatively evaluated the potential of using an active IRT in conjunction with an artificial heat source to enhance thermal contrast in defective areas compared to a passive IRT that uses no external excitation energy source (Lerma et al. 2018). With the addition of reliable metrics for quantitative assessment of building performance or the quality of building construction, the effectiveness of IRT can be further improved (Guo 2015). In addition, IRT can be combined with terrestrial laser scanning, i.e., LiDAR (Light Detection and Ranging), to produce a better model resolution and accuracy compared to images obtained in the visible wavelength, i.e., with RGB-D camera (Alba et al. 2011) or from SFM (Structure-from-motion model) (Ham and Golparvar-Fard 2013).

Overall, IRT can detect heat losses or gains through the building envelope and provide detailed information on building defects and anomalies such as missing, damaged or improperly installed thermal insulation (wet and dry), thermal bridge, and air leakages (Balaras and Argiriou 2002; Barreira and de Freitas 2007; Fokaides and Kalogirou 2011; Kirimtat and Krejcar 2018; Kylili et al. 2014). In IRT investigations, missing insulation appears as light/dark areas with distinct edges outlining the non-insulated area. A thermal bridge is an area with higher thermal conductivity than the surrounding, and it appears as light/dark areas with linear features as they are often caused by structural components of the building that penetrate the insulation (Balaras and Argiriou 2002; Craveiro et al. 2018; Guo 2015).Thermal bridges are also formed due to discontinuities or gaps in the insulation material (Gorse and Johnston 2012). Observed cracks in building walls can lead to air infiltration or exfiltration (Balaras and Argiriou 2002), thus affecting the movement of pollutants across the building walls and the presence of pollutants within the building. All of these deficiencies have potential effects on IAQ.

All these mentioned building and indoor air investigation techniques, i.e., indoor air quality investigation, questionnaires, and spatially resolved infrared thermography imaging provide valuable insights into IAQ and building conditions, but typically are used separately, especially when it comes to infrared thermography or its combination with terrestrial laser scanning. We suggest that the integration of terrestrial laser scanning and infrared thermography with traditional air sampling and questionnaire usage in IAQ studies brings new opportunities for identifying and diagnosing various housing-related health and IAQ issues. However, the use of such an integrated approach to detect housing-related health issues has not yet been explored.

Thus, the main goal of this pilot-level project was investigate the potential to use, integrate, and correlate three data streams (i.e., traditional indoor air quality investigation, use of questionnaires and spatially resolved infrared thermography imaging) during IAQ investigation in residential multi-apartment buildings and then use the integrated data to investigate building deficiencies and their role in indoor air quality and residents' health.

2. Methodology

2.1 Study sites

The study was designed as an evaluation of building attributes, including potential deficiencies, indoor air quality, and residents' perceptions about their health and building conditions. We partnered with WHEDco (Women's Housing and Economic Development Corporation; Bronx, NY) to assess two high-rise affordable housing buildings they own: Building 1 located in the Bronx, New York, and Building 2 located in South Bronx, New York. Both buildings house low-income and otherwise vulnerable populations who are predominantly African American, Hispanic or Latino. Building 1 was built in the 1920s, retrofitted in 2006 and contains 132 apartments. Building 2 is an EPA Energy Star certified building that was built in 2009 and contains 128 apartments. A more detailed description of Building 2 is provided elsewhere (Jordán-Cuebas et al. 2018; Table 2). The terms "apartment" and "household" are used interchangeably.

Figure 1. Field study sites. a) Building 1 and b) Building 2 (Photo credits: Google Maps and WHEDco: Women's Housing and Economic Development Corporation; Bronx, NY).

2.2 Field Data Collection

In Building 1 (Figure 1a), data were collected in four apartments in February 2016. Additional data from 15 apartments in the same building were collected during the summer season of 2014, but they were not used for this study because the temperature difference between indoors and outdoors turned out to be too low for the infrared detection system to work properly. The lack of temperature difference was at least partially due to windows kept predominantly open during summer. In Building 2 (Figure 1b), data were collected in 16 apartments during four data collection trips from 3/14/2015 to 3/20/2015. For all 20 apartments, the collected data included infrared images, terrestrial LiDAR data, digital images of the exterior building structure and interior walls of apartments, indoor humidity and temperature, mass and number concentrations of various airborne particulate matter fractions and real-time weather data from a nearby weather station. Questionnaires investigating residents' health and their perception of building conditions were also administered.

2.3 Infrared thermography, laser scanning, and sensor data fusion

This study combined terrestrial laser scanning using the FARO Laser Scanner Focus3D (FARO Technologies, Korntal-Münchingen, German) with Light Detection and Ranging (LiDAR) technology, and infrared scanning using the FLIR T650sc camera (FLIR Systems, 27700 SW Parkway Ave. Wilsonville, OR, USA). The research methodology when using this combination of instruments is explained in detail elsewhere (Guo 2015). The developed methodology was used to generate a 3D thermal model, and the overall flow diagram of the process is shown in Figure S1 in Supplemental Information (SI). Briefly, the steps involved in producing the needed 3D thermographic data were: 1) collection of infrared (IR) data that include both color and temperature information for every point in the image and processing of the image into a data matrix that preserves temperature information; 2) terrestrial laser scanning of the buildings to obtain three dimensional information about the buildings and use that data to generate 3D point clouds; 3) stitching of infrared images (Figure 2a) and their temperature-based segmentation (Figure 2b) to isolate and pinpoint areas with different temperatures; 4) projection of infrared temperature segmentation results to 3D point clouds (Figure 3a); and 5) 3D thermal point cloud segmentation (Figure 3b) to detect structural elements and quantify building anomalies or attributes that are relevant to building performance.

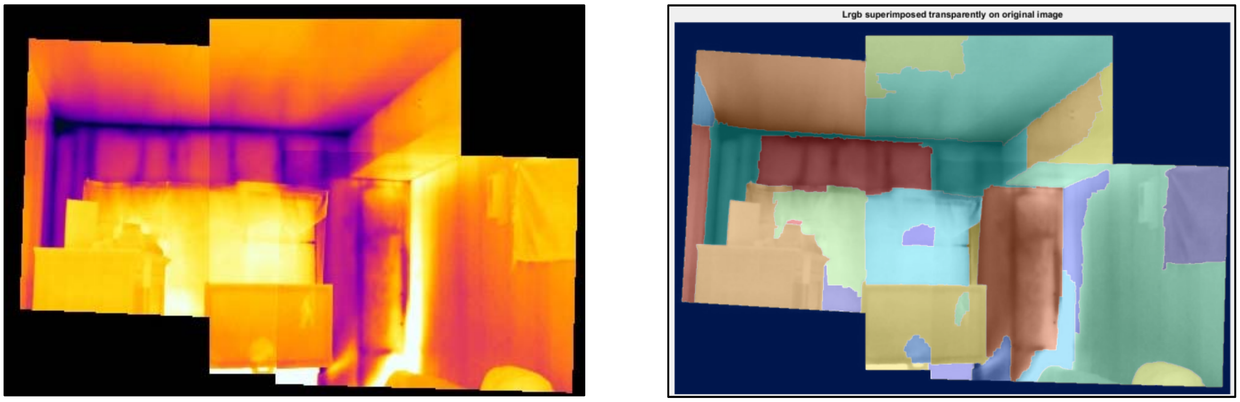

Figure 2. (a) Stitching of indoor infrared images; (b) Results of infrared temperature-based segmentation.

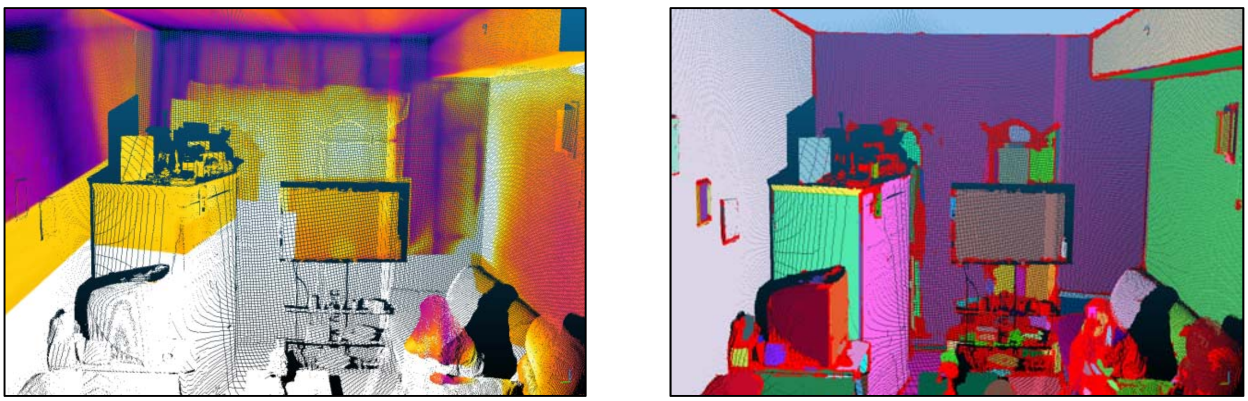

Figure 3. (a) 3D thermal point cloud model; (b) Segmented 3D point cloud.

2.4 IAQ measurements

IAQ was measured in 20 participating apartments (4 in Building 1 and 16 in Building 2). For all days when indoor measurements were performed, equivalent measurements were performed outdoors. Temperature, relative humidity, carbon monoxide, and carbon dioxide were measured and data-logged for 45-60 min using an IAQ-Calc Indoor Air Quality Meter 7525 (TSI Inc., Shoreview, MN), a direct reading instrument designed for indoor air studies.

Particle size distribution was measured using AeroTrak Handheld Particle Counter 9306 (TSI, Inc.), which counts particles in five size channels ranging from 0.3 to 10 µm, and the last channel counts particles > 10um. Total particle number concentration was measured using a P-Trak condensation particle counter (TSI Inc.), which counts all particles larger than 20nm in size. These direct reading instruments were operated for 45-60 min in each apartment, and average values, as well as other statistics (min and max values, 5^{th} - 95^{th} percentile range), were recorded. In the subsequent text, the number concentration of particles below 300 nm refers to the P-Trak-measured concentration minus the concentration of particles

> 300 nm measured by the OPC; and the particle number concentration above 300 nm refers to the total particles measured by an OPC. While many studies define ultrafine particles as particles < 100 nm (Martins et al. 2010; Mendes et al. 2018; Penttinen et al. 2001; Seigneur 2009; Tobías et al. 2018), some studies use a broader definition and include particles up to 300 nm in diameter (Lee et al. 2017) For the purpose of this paper, the term ultrafine particles will refer to particles smaller than 300 nm. It has been reported that particles smaller than 300 nm contribute to over 99% of the total particles number concentration in urban streets (Kumar et al. 2009, 2014); such particles also penetrate deeply into the human respiratory system and are of health concern (Baldauf et al. 2016).

The mass concentration of airborne particulate matter in each apartment was measured and data-logged using Dustrak DRX Aerosol monitor (TSI, Inc.) for 45-60 min. This instrument provided real-time measurements of airborne particle concentrations corresponding to PM_1, $PM_{2.5}$, Respirable (PM_4), PM_{10}, and total PM size fractions. Twenty-four hr $PM_{2.5}$ concentrations were measured using an SKC Inc. (Eighty Four, PA) Personal Modular Impactor with 2.5 µm cut size and 2 µm pore size 37 mm PTFE filter (SKC Inc.). The required flow rate of 3 L/min was provided by a calibrated XR5000 pump (SKC Inc.). During sample collection, the impactor was mounted on a tripod, connected to a pump enclosed in a noise reducing protective pouch (SKC Inc.) and left in each sampling location for 24 hrs. The collected particle mass and the corresponding airborne mass concentration were determined by weighing each filter before and after sampling. Prior to each weighing, the filters were equilibrated in a weighing room at a steady temperature (20-22℃) and relative humidity (40%) for at least 72 hours. In the subsequent text, the airborne mass concentration of $PM_{2.5}$ refers to that measured by the impactor. The mass concentration of particles > 2.5 µm was determined based on DRX measurements: total PM measured by DRX minus $PM_{2.5}$ measured by DRX.

2.5 Interviews

We conducted individual interviews with an adult, who was present in the investigated apartment, and with building owners/operators from June 2014 through March 2016 in accordance with IRB-approved questionnaires and human subject research protocols (14-327M). The study participants from 20 households were asked about their perception of building quality and comfort, including air quality, concerns related to living conditions, household activities that could impact indoor air quality, and health problems in their family, such as asthma events and other illnesses.

2.6 Statistical analysis

Since the indoor air quality dataset was non-normally distributed, non-parametric tests were performed for the analysis. The median, 25th and 75th percentile, minimum and maximum values are presented since all the measured data were not normally distributed. The correlations between independent non-linear variables (missing insulation in terms of square feet and percentage of the area relative to the outer wall area) were obtained through Spearman correlation, r_s. Independent ordinal variables were associated by gamma correlation, G. A G value <0.3, 0.3 – 0.6, >0.6 was considered to have weak, moderate and strong associations, respectively (Table 14.2 in Healey 2011) . When data were stratified into two or three groups, the difference of the mean between the groups was analyzed by the Mann-Whitney U test and Kruskal- Wallis H tests, respectively. For many IAQ parameters, ratios of indoor to outdoor values (I/O) were determined. I/O values above 1 suggest prominent indoor sources and values below 1 suggest a higher contribution by outdoor sources. Statistical analysis was performed using IBM SPSS Statistics 24.0, and statistical significance was accepted at p-values <0.05 and borderline significance at p-values <0.1.

3. Results and Discussion

3.1 Infrared thermography

A total of 1609 infrared images were captured for 20 apartments in two buildings. These infrared images were integrated with LiDAR data to generate 3D thermography data. The integrated data were used to locate and identify building anomalies using 3D thermal model. Table S1 in SI illustrates building defects that were detected and quantified. Since our preliminary analysis showed that missing thermal insulation (MI) resulted in the highest correlation with IAQ observations and questionnaire data, we focused on this building deficiency.

Missing thermal insulation was detected using IR cameras as a patch with well-defined edges (Balaras and Argiriou 2002) (Figure 4). The RESNET (Residential Energy Services Network) Interim Guidelines for Thermographic Inspections of Buildings provides standards for the use of IRT in residential and light commercial buildings including information on identification of building anomalies (RESNET 2012). According to the RESNET standards and FLIR thermal imaging guidebook (FLIR System 2011), a minimum temperature difference of 11°C (18°F) between the external and internal surfaces is required during inspection to obtain sufficient information about missing or poor insulation. Once all the missing and poor insulation areas were detected and located, a 3D thermal point cloud was used to determine the physical size of each deficiency. For each apartment, the missing insulation was measured in square feet as well as a fraction (or percentage) of the exterior wall. The two variables had a high correlation: r_s= 0.992, p <0.001. The Insulation Grading Standard designed by RESNET was used to grade the insulation condition of each apartment. The standard classifies the insulation condition into three categories:

- Grade I: no anomalies found using an infrared camera
- Grade II: 0.5% to 2% of insulation missing for all inspected walls
- Grade III: 2 % to 5% of insulation missing for all inspected walls

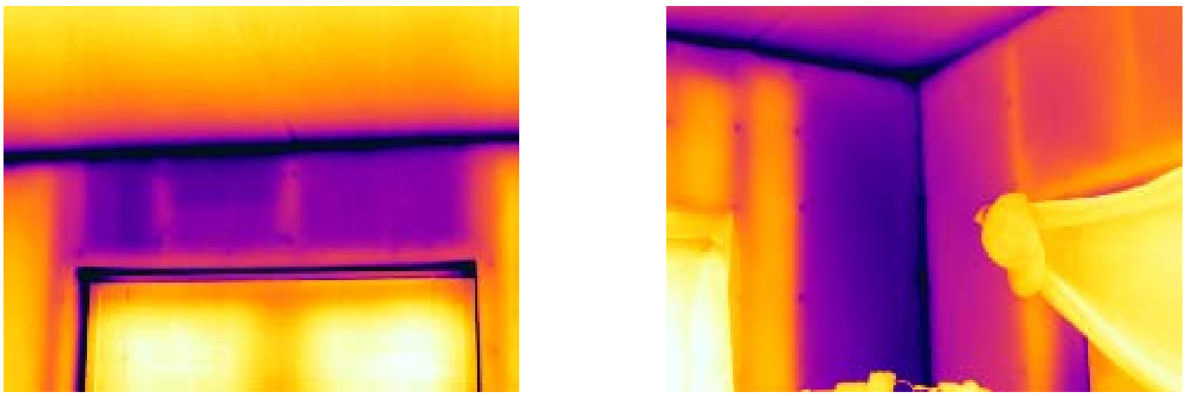

Figure 4. Missing insulation on exterior walls indicated by the cooler colors (dark purple/black) in the infrared images.

In some apartments, the percentage of external wall area with missing insulation was higher than the top range of Grade III. Thus, we added Grade IV to classify the apartments with more than 5% of missing insulation (MI). Given that there were only 20 data points, for further analysis, the apartments were stratified into two groups according to MI % levels: apartments that had less than 5% of MI ("low group") and those that had more than 5% of MI ("high group"), and their summary statistics are presented in Table 1. The median MI percentage value for "low" group was 0.77%, and for the "high" group was 9.91%; and the difference was statistically significantly different, according to Mann Whitney U test (U=0.00, p <0.001).

Table 1. Descriptive statistics of missing insulation levels in both ft^2 and percentage of the wall area.

Group		N	Mean (Std. Dev.)	Median (Std. Dev.)	Minimum	Maximum
"Low" (Missing insulation below 5%)	Missing insulation (ft^2)	14	3.24 (2.97)	2.22 (2.97)	0.45	9.31
	Missing insulation (%)		1.25 (1.18)	0.77 (1.18)	0.13	3.65
"High" (Missing insulation above 5%)	Missing insulation (ft^2)	6	26.48 (10.73)	29.86 (10.73)	13.0	36.53
	Missing insulation (%)		10.98 (5.54)	9.91 (5.54)	5.25	19.62

3.2 Association of missing insulation with particulate matter presence

Table 2. Particulate matter concentrations and their indoor/outdoor ratios. Number concentrations were measured for 45-60 min using direct-reading instruments, while $PM_{2.5}$ mass concentrations were measured for 24 hours using filter sampling; the latter is denoted by *.

Variable	N	Median (25th, 75th percentiles)	Minimum	Maximum
Number concentration of ultrafine particles (<300nm) (#/m^3)	20	1.50×10^{10} (7.31×10^{9}, 2.72×10^{10})	2.64×10^{9}	9.86×10^{10}
Number concentration of particles >300nm (#/m^3)	20	2.19×10^{7} (9.22×10^{6}, 5.33×10^{7})	1.38×10^{6}	5.53×10^{8}
Mass concentration of $PM_{2.5}$ particles (µg/m^3) *	20	28.37 (19.07, 57.61)	7.23	96.29
Mass concentration of particles >$PM_{2.5}$ (µg/m^3)	20	24.57 (16.01, 37.87)	7.51	45.26
Indoor/Outdoor ratio of ultrafine particle number concentration (<300 nm)	20	0.85 (0.57, 1.47)	0.35	13.14

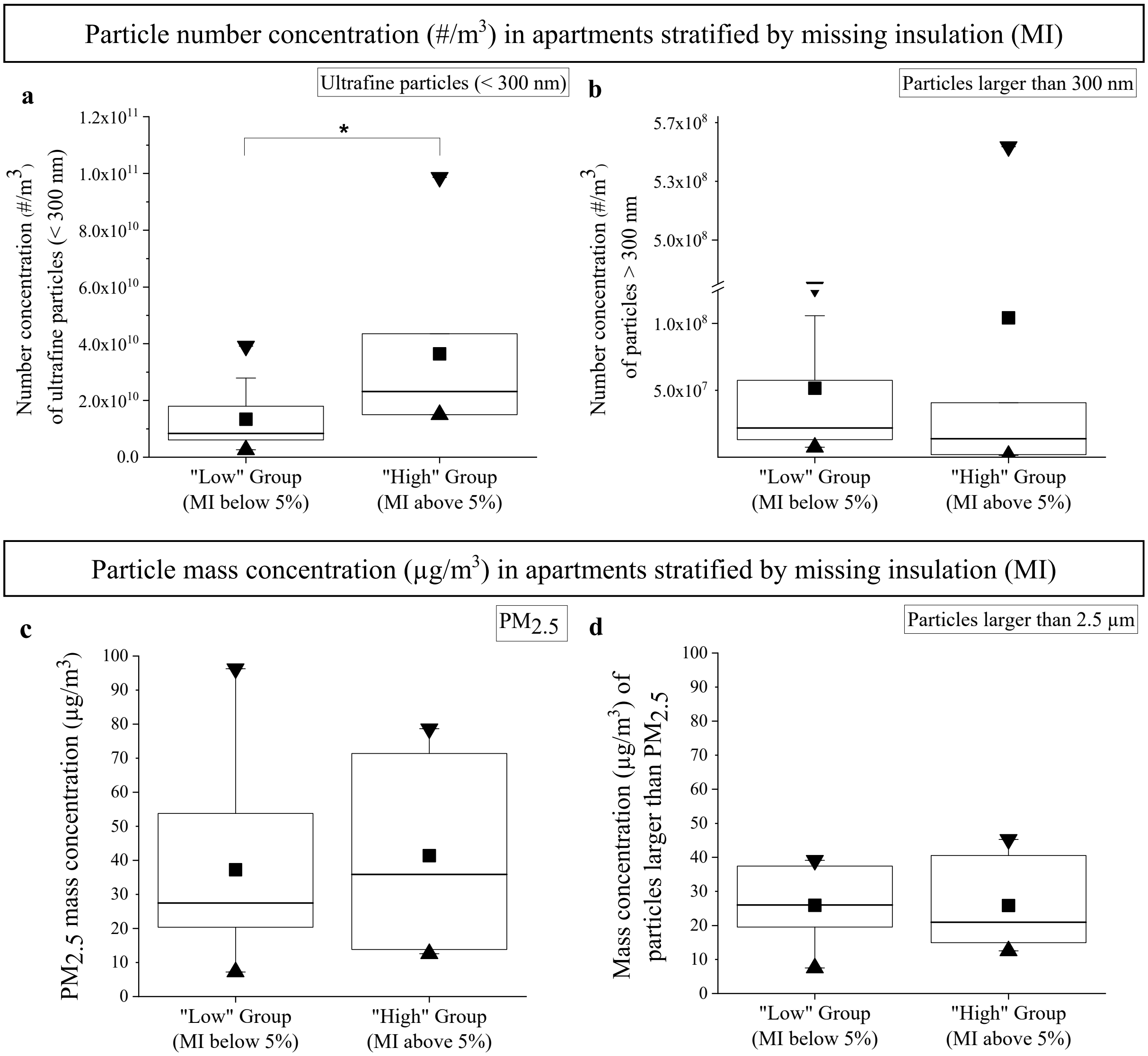

Figure 5. Airborne particle characteristics in investigated apartments stratified by missing insulation groups: "low" (n=14) and "high" (n=6). a. and b: Number concentration of particles smaller and larger than 300 nm, respectively. c. and d: Mass concentration of $PM_{2.5}$ particles and larger particles, respectively. The asterisk (*) represents a statistically significant difference ($p<0.05$) between the groups. The upward facing triangles and downward facing triangles represent 1st and 99th percentile of the data, respectively; the whiskers represent 1.5x of interquartile range; the square represents the mean; the lower, middle and upper lines of each box plot are 25th percentile, median, and 75th percentile of the data, respectively.

Initial analysis showed that the number concentration of all particles (d > 20nm) was correlated with missing insulation with borderline significance ($p = 0.069$ for the area in ft^2 and $p = 0.098$ for %; Figure S2). In order to investigate a possible correlation of missing insulation with ultrafine particle concentration, the particle number concentration was separated into number concentration of particles smaller than 300 nm and the number concentration of particles larger than 300 nm. The cut-off size of 300 nm was based on the physical limitation of the instrument. As mentioned above, for the purpose of this paper, particles <300 nm will be called ultrafine particles. The descriptive statistics of particle number and mass concentrations are shown in Table 2. The number concentration of ultrafine particles represented 99.7% of the total particle number concentration (larger than 20 nm) with median value of 1.50×10^{10} #/m^3 (25th %: 7.31×10^9 #/m^3, 75th %: 2.72×10^{10} #/m^3). The indoor/outdoor ratio of ultrafine particle concentrations (<300 nm) ranged from 0.35 to 13.14. The mass concentration of $PM_{2.5}$, or fine particles, had a median concentration of 28.37 μg/m^3 (25th %: 19.07 μg/m^3, 75th %: 57.61 μg/m^3). The mass concentration of particles >$PM_{2.5}$ represented 30% of the total particle mass concentration measured by the Dustrak DRX Aerosol monitor (TSI, Inc.) with a median value of 24.57 μg/m^3 (25th %: 16.01 μg/m^3, 75th %: 37.87 μg/m^3).

The number concentrations of ultrafine particles in the two apartment groups according to their missing insulation percentage was significantly different as per Mann Whitney U test ($U= 15.0$, $p = 0.013$) with a median concentration value of 8.39×10^9 #/m^3 for "Low" group and 2.32×10^{10} #/m^3 for "high" group (Figure 5a). The particle number concentration for "low" group ranged from 2.64×10^9 to 3.92×10^{10} #/m^3 (25th %: 5.69×10^9 #/m^3; 75th %: 1.99×10^{10} #/m^3), while for the "high" group, the concentration ranged from 1.50×10^{10} #/m^3 to 9.86×10^{10} #/m^3 (25th %: 1.5×10^{10} #/m^3; 75th %: 5.73×10^{10} #/m^3). The number concentrations of particles larger than 300 nm stratified into the "low" and "high" groups were not significantly different as per Mann Whitney U test ($U= 32.0$, $p = 0.222$) (Figure 5b). The median values here were similar (2.32×10^7 #/m^3 for "low" group and 2.19×10^7 #/m^3 for "high" group). This result suggests that the indoor presence of ultrafine particles is associated with missing insulation, likely due to increased penetration of such particles from outdoors (Nazaroff 2004).

When $PM_{2.5}$ indoor mass concentrations were stratified according to missing insulation levels, the difference was not significantly different as per Mann Whitney U test ($U = 38.0$, $p = 0.390$) (Figure 5c) with median value of 27.48 μg/m^3 for "low" group and 35.87 μg/m^3 for "high" group. The same could be said about the mass concentration of particles larger than 2.5 μm as per Mann Whitney U test ($U = 41.0$, $p = 0.484$) (Figure 5d) that showed median values of 26.04 μg/m^3 and 20.94 μg/m^3 for "low" and "high" groups, respectively. Since particle mass is proportional to the cube of particle diameter, ultrafine particles do not contribute much to $PM_{2.5}$ mass (Matson 2005), and the difference in number concentration of particles below 300 nm did not affect the difference in $PM_{2.5}$ concentrations.

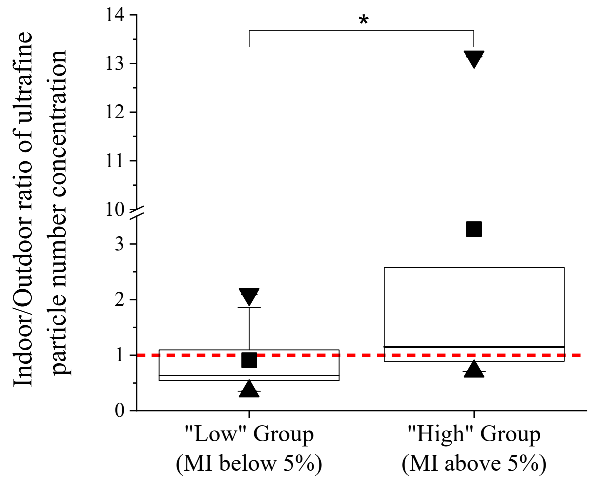

Figure 6. The indoor/outdoor ratio of number concentration of ultrafine particles stratified by missing insulation (%) groups. The dotted red line represents the indoor/outdoor ratio equal to 1. The asterisk (*) represents a statistically significant difference ($p<0.05$) between the groups. The upward facing triangles and downward facing triangles represent 1st and 99th percentile of the data, respectively; the whiskers represent 1.5x of interquartile range; the square represents the mean; the lower, middle and upper lines of the box plot are 25th percentile, median, and 75th percentile of the data, respectively.

We also compared indoor/outdoor (I/O) ratios of number concentrations of ultrafine particles in apartments with different levels of missing insulation. The median I/O value in the "high" group (50th %: 1.15) was significantly higher than that in the "low" group (50th %: 0.63) ($U = 19.0$, $p = 0.029$) (Figure 6). Particles generated indoors, such as those produced by occupant behavior, as well as those that penetrate from outdoors contribute to the overall presence and accumulation of particles indoors. Missing wall insulation seems to aid particle penetration from outdoors thus increasing the presence of particles indoors.

If one presumes the same particle generation indoors by both the "low" and the "high" groups, then the I/O difference between the two groups could be attributed to the accumulation of particles that penetrated from outdoors. At the same time, it is known that various indoor combustion processes, e.g., smoking, generate ultrafine particles. Thus, individual residents' behavior could substantially affect the presence of particles indoors. Therefore, it was important to match the apartments according to their potential to generate ultrafine particles and then investigate the presence of ultrafine particles as a function of missing insulation. Here, apartments were divided into categories depending on the presence or absence of the following indoor activities: smoking, burning of either candles or incense, and smoking or burning of either candles or incense (this category is later referred to as “indoor combustion sources”). The information on residents’ indoor activities was collected during the interviews, and the data are shown in Table 3. The questionnaire asked only about the presence of those combustion sources but not about their strength, e.g., a number of cigarettes smoked or the frequency of smoking. Visual confirmations of these indoor combustion sources were not recorded by the interviewer. The observed airborne concentrations of ultrafine particles in apartments with and without the above-mentioned indoor combustion sources were stratified according to their missing insulation level, and the data are presented in Figure 7.

In apartments with no smoking (n=14) with a subset of 7 apartments where candles or incense was burnt (Figure 7a), the number concentration of ultrafine particles in the “high” group (n = 5 with 3 candles and incense burners) had a median value of 1.87 $x10^{10}$ #/m^3 (25^{th} %: 1.5 x 10^{10} #/m^3, 75^{th} %:3.56 x 10^{10} #/m^3), and it was significantly higher than that in the “low” group (n = 9 with a subset of 4 candles or incense burners), which had a median value 7.63 $x10^9$ #/m^3 (25^{th} %: 5.0 x 10^9, 75^{th} %: 1.28 x 10^{10}), with U= 5.0 and p = 0.010.

Apartments with no candles or incense burnt (n=8) with a subset of 1 smoker (Figure 7b) had a similar relationship of having significantly higher number concentration of ultrafine particles in the “high” group (n = 2 with no smokers; median = 3.11 x 10^{10} #/m^3; 25^{th} %: 1.87 x 10^{10} #/m^3, 75^{th} %: 4.36 x 10^{10} #/m^3) than the “low” group (n = 6 with a subset of 1 smoker; median = 7.56 x 10^9 #/m^3; 25^{th} %: 5.55 x 10^9 #/m^3, 75^{th} %: 8.85 x 10^9 #/m^3) (U= 1.0, p = 0.048). We further looked at apartments with none of the indoor combustion sources (n = 7, Figure 7c) and the above stated relationship persisted and was significantly different. Here, the “low” group (n= 5) had a median particle number concentration of 7.2 x 10^9 #/m^3 (25^{th} %: 5.0 x 10^9 #/m^3, 75^{th} %: 8.39 x 10^9 #/m^3) which was higher than that for the “high” group (n = 2) with a median of 3.11 x 10^{10} #/m^3 (25^{th} %: 1.87 x 10^{10} #/m^3, 75^{th} %: 4.36 x 10^{10} #/m^3) (U= 0.0, p = 0.027). This suggests that the presence of particles below the size of 300nm in apartments with no combustion or minimal combustion sources was significantly affected, higher, if high levels of missing insulation was detected.

On the other hand, in the presence of any one of the following particle sources, such as smoking (n = 6 with a subset of 5 candles or incense burners, Figure 7d), candles or incense burnt (n = 12 with a subset of 5 smokers, Figure 7e) or any two indoor combustion source categories (n = 13, Figure 7f), the indoor particle number concentration was not dependent on the levels of missing insulation. This suggests that the production of particles by the combustion sources overwhelmed the influx of ultrafine particles due to missing insulation and, thus, no difference was observed.

In order to check the influence of other common indoor particle sources on the presence of particles, the particle presence was analyzed as a function of cooking frequency in each apartment. Based on questionnaire data, 2 residents cooked once a day, 8 residents cooked twice a day, and 10 residents cooked a day thrice. According to Kruskal-Wallis H test, we found that cooking didn't have a significant effect on the number concentration of ultrafine particles (χ^2 (2) = 2.60, p = 0.272) or above 300nm (χ^2 (2) = 3.95, p = 0.139).

Further analysis was performed to investigate the association between missing insulation and residents' perception of indoor air quality. Residents were asked whether they thought the air in their apartments was dusty. Out of the 15 apartments perceived by the residents as being dusty, 5 apartments had missing insulation above 5%. Association between apartments perceived as being dusty and high levels of MI was moderate, with G value of 0.333 and, yet not significant (p = 0.543). Reports on sensing any bad odors related to chemicals or garbage from the hallway or inter-apartment spaces were also recorded in the questionnaire but found to have no association with MI levels (G = -0.286, p = 0.556).

Table 3. Questionnaire data on the presence of combustion sources indoors.

Report (n= 20)	**Yes, % (n)**	**No, % (n)**
Smoking indoors	30 (6)	70 (14)
Candles or incense burnt indoors	60 (12)	40 (8)
Indoor combustion sources (smoking or candles/incense)	65 (13)	35 (7)

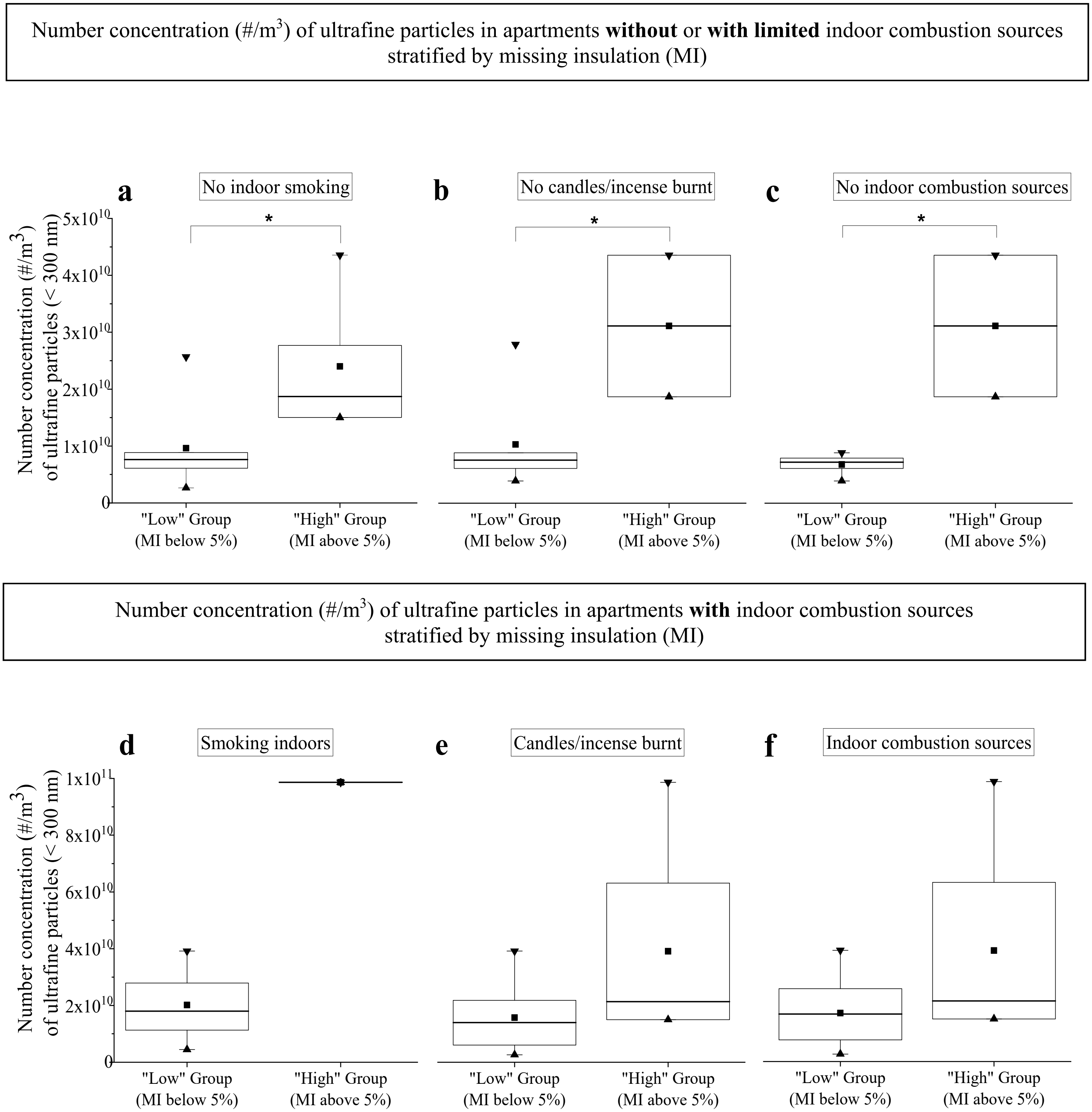

Figure 7. Number concentration (#/m^3) of ultrafine particles stratified by levels of missing insulation (%) with respect to the presence of combustion sources. a. Apartments with no smoking reported ("low" group: n = 9, "high" group: n = 5). b. Apartments with no candles or incense burnt ("low" group: n = 6, "high" group: n = 2). c. Apartments with no smoking, candles or incense burnt ("low" group: n = 5, "high" group: n = 2). d. Smoking reported indoors ("low" group: n = 5, "high" group: n = 1). e. Candles or incense burnt indoors ("low" group: n = 8, "high" group: n = 4). f. Smoking, candles or incense burnt indoors ("low" group: n = 9, "high" group: n = 4). The upward facing triangles and downward facing triangles represent 1st and 99th percentile of the data, respectively; the whiskers represent 1.5x of interquartile range; the square represents the mean; the lower, middle and upper lines of the box plot are 25th percentile, median, and 75th percentile of the data, respectively.

3.3 Association between missing insulation and apartment location

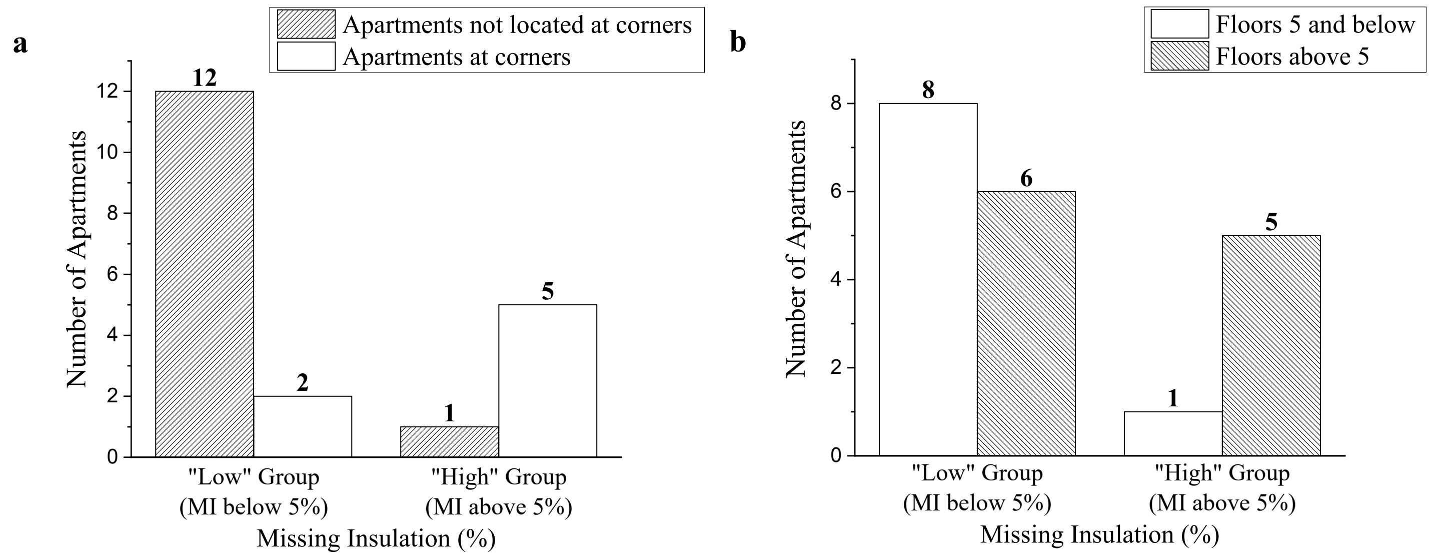

Figure 8. Association between missing insulation (%) and apartment location. a. Association between corner apartments (7/20 apts.) and the level of missing insulation (%). b. Association between apartments located on floors above 5 (11/20 apts.) and the level of missing insulation.

We further investigated whether the apartment location was correlated with missing insulation. Apartments located in corners (7/20 apts.) were strongly and significantly (G= 0.935, p = 0.002) correlated with the high percentage of missing insulation (Figure 8a). Specifically, out of six apartments in the "high" group, five were corner apartments. As a consequence, corner apartments had a higher number concentration of ultrafine particles compared to non-corner apartments: the median number concentration of 1.87×10^{10} #/m^3 (25^{th} %: 1.5×10^{10} #/m^3, 75^{th} %: 3.92×10^{10} #/m^3) for corner apartments and the median number concentration of 7.92×10^9 #/m^3 (25^{th} %: 5.28×10^9 #/m^3, 75^{th} %: 2.19×10^{10} #/m^3) for non-corner apartments; the difference was statistically significant (U= 17.0, p = 0.012). The number concentration of particles larger than 300nm had a median concentration of 7.49×10^6 #/m^3 (25^{th} %: 1.95×10^6 #/m^3, 75^{th} %: 4.07×10^7 #/m^3) in corner apartments, and it was lower compared to non-corners apartments with a median number concentration of 2.33×10^7 #/m^3 (25^{th} %: 1.42×10^7 #/m^3, 75^{th} %: 6.88×10^7 #/m^3); the difference was borderline significant (U= 28.0, p= 0.083).

The number of apartments where residents noticed cracks (n= 10) did not depend on apartment location with respect to corners (4/10 residents noticed cracks in corner apartments vs. 6/10 residents who noticed cracks in non-corner apartments; G= 0.217, p = 0.637). The indoor temperature was marginally lower in corner apartments (mean = 75.17 ± 4.32 °F; median = 75.5 °F; 25th %: 71.7 °F, 75th %: 78.51 °F) when compared to non-corner apartments (mean = 75.99 ± 5.41 °F; median = 76.52 °F; 25th %: 74.97 °F, 75th %: 79.28 °F), but not significantly so (U= 38.0, p = 0.276). The apartment R-values, which are indicators of an ability by an indoor space to maintain temperature, were lower in corner apartments (mean = 1.09 ± 0.54; median = 0.94; 25th %: 0.85, 75th %: 1.61) compared to non-corner apartments (mean = 1.49 ± 1.21; median = 1.21; 25th %: 0.61, 75th %: 2.05), yet not significantly so (U = 36.0, p =0.226).

Residents in corner apartments were more likely to burn either candles or incense indoors compared to non-corner apartments (G= 0.750, p = 0.047). Seven out of 8 apartments which didn't burn either candles or incense were non-corner apartments. However, the apartments where residents burnt either candles or incense indoors were equally distributed between the corner and non-corner locations at 6 apartments each. Smoking had little or no influence on the ultrafine particle number concentration in corner apartments (G = 0.429, p = 0.374). An equal number of smokers were recorded in both corner (n=3) and non-corner (n=3) apartments. 6/7 of the corner apartments reported indoor combustion sources (G = 0.674, p = 0.105). However, there was also an almost equal number of apartments that reported indoor combustion sources in non-corner apartments (7/13 apts.).

The apartments located on the fifth floor or below (n= 9) had lower amounts of missing insulation (mean = median = 1.29%; 25th %: 0.33%, 75th %: 3.62%) compared to apartments located on floors six and higher (median = 2.31%; 25th %: 0.7%, 75th %: 7.12%); the association was strong yet only borderline significant (G = 0.739, p = 0.062) (Figure 8b).

3.4 Association of asthma with missing insulation

Table 4. Questionnaire data on asthma prevalence

Report (n= 20)	**Yes, % (n)**	**No, % (n)**
History of asthma for anyone in the apartment	60 (12)	40 (8)
Reported asthma attacks for anyone in the apartment in the last 12 months	30 (6)	70 (14)

The Bronx residents are known to have a high prevalence of asthma (DiNapoli 2014; Karetzky 1977; Maantay 2007; Warman et al. 2009), and, therefore, several asthma-related questions were included in our questionnaire. The summary of responses is presented in Table 4. We investigated several possible associations between the number of asthma cases reported by residents in the past 12 months and our-measured environmental variables. When the number of asthma attacks (n=6) was stratified according to missing insulation levels, the association was positive but not significant ($G = 0.111$, $p = 0.834$). The "low" group had 4/6 cases, and the "high" group had 2/6 cases. The missing insulation percentage in apartments where residents did not report asthma attacks in the past 12 months (n=14) ranged from 0.13% to 12.71% (median = 1.53%, 25^{th} %: 0.36%, 75^{th} %: 5.66%), while the missing insulation percentage ranged from 0.55 % to 19.62% (median = 1.57%, 25^{th} %: 0.66%, 75^{th} %: 15.63%) in the apartment where residents reported asthma (Figure 9a). The median levels and the minimum values were similar for both groups, but the maximum value was 7% higher on an absolute scale in apartments where asthma attacks were reported.

We further investigated whether there was an association between asthma attacks reported in the last 12 months and PM levels indoors. The number concentration of ultrafine particles was significantly higher in the group with asthma attacks ($U= 19.0$, $p = 0.029$), with median number concentration of 2.3×10^{10} #/m^3 (25^{th} %: 1.07×10^{10} #/m^3; 75^{th} %: 5.73×10^{10} #/m^3) for the "Asthma" group compared with the median value of 1.15×10^{10} #/m^3 (25^{th} %: 5.69×10^{9} #/m^3; 75^{th} %: 2.05×10^{10} #/m^3) for the "No Asthma" group (Figure 9b). A similar significant association was seen between reported asthma attacks and number concentration of particles larger than 300 nm ($U= 3.0$, $p = 0.001$). Here, the group with reported asthma attacks had in their apartments a median particle number concentration almost 6x higher compared to the non-asthma group: 8.16×10^{7} #/m^3 vs. 1.42×10^{7} #/m^3. The $PM_{2.5}$ levels also showed a significant association with asthma attacks reported in the last 12 months ($U= 18.0$, $p = 0.024$) (Figure 9c). The median $PM_{2.5}$ mass concentration in apartments with asthma (median = 51.8 µg/m^3; 25^{th} %: 34.0 µg/m^3, 75^{th} %: 78.26 µg/m^3) was twice as high as the median $PM_{2.5}$ concentration in apartments with no reported asthma (median= 23.99 µg/m^3; 25^{th} %: 13.51 µg/m^3, 75^{th} %: 41.80 µg/m^3). Additionally, occupant behavior, such as smoking indoors (n=6) was also strongly and significantly associated with asthma reports ($G= 0.846$, $p = 0.027$, Figure 9d). Out of 14 apartments that did not report asthma attacks, smoking was reported only in 2 apartments, while four residents in 6 apartments with asthma attacks reported smoking indoors; that helps explain higher $PM_{2.5}$ levels in apartments with asthma. Additionally, residents in 1 of 6 apartments who reported asthma attacks didn't smoke indoors but had as much as 14.30% of insulation missing. This specific resident also did not report the burning of candles or incense.

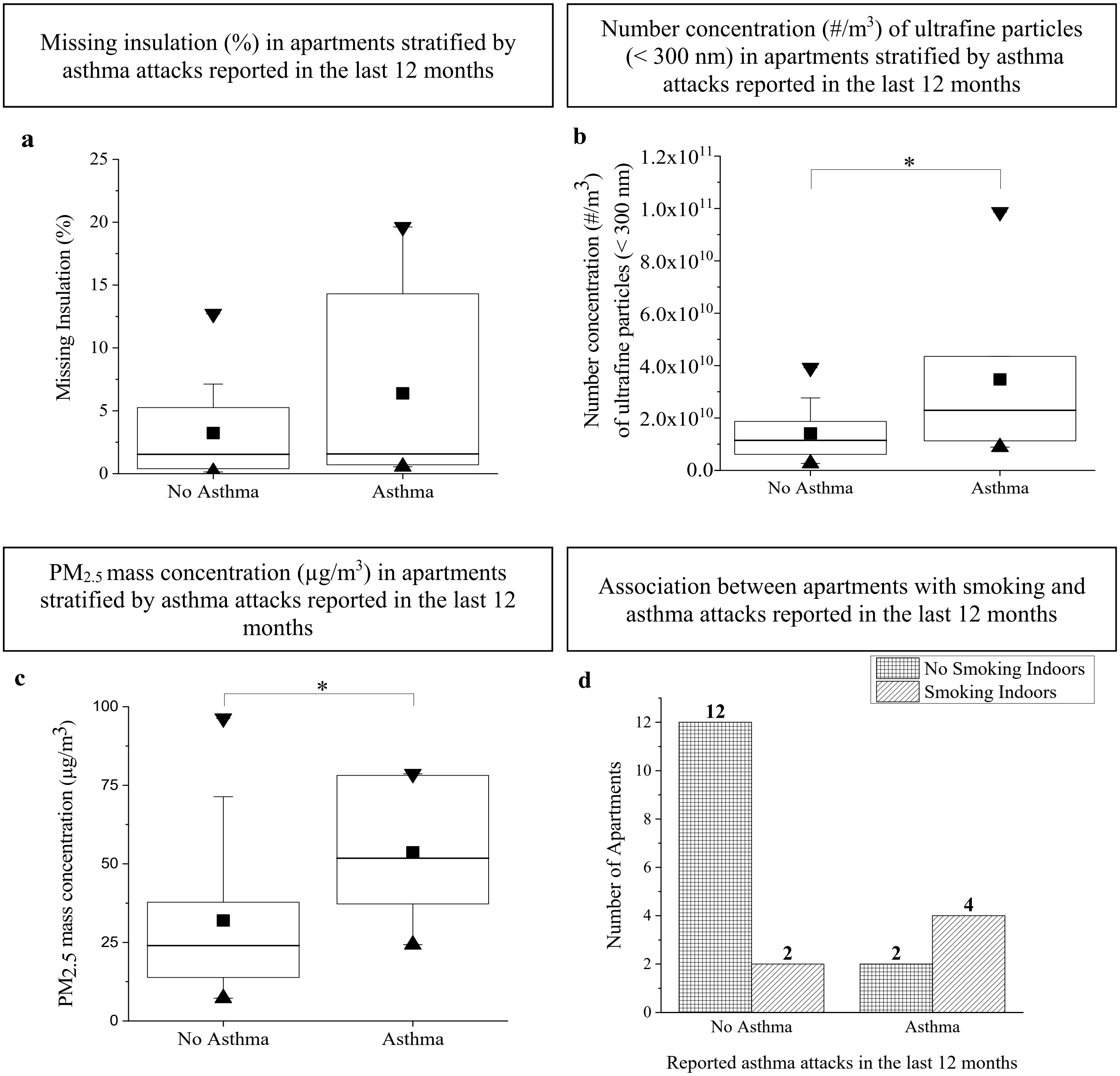

Figure 9. a. Missing insulation (%) in apartments stratified by reported asthma attacks in the last 12 months. b. Number concentration of ultrafine particles stratified by reported asthma attacks in the last 12 months. c. $PM_{2.5}$ mass concentration ($\mu g/m^3$) stratified by reported asthma attacks in the last 12 months. d. Association between smoking indoors and reported asthma attacks in the last 12 months. The asterisk (*) represents a statistically significant difference ($p<0.05$) between the groups. The upward facing triangles and downward facing triangles represent 1st and 99th percentile of the data, respectively; the whiskers represent 1.5x of interquartile range; the square represents the mean; the lower, middle and upper lines of the box plot are 25th percentile, median, and 75th percentile of the data, respectively.

The overall prevalence of asthma cases (n=12) was not associated with the number concentration of ultrafine particles (U= 46.0, p = 0.439). However, the number concentration of particles larger than 300 nm was borderline positively associated (U= 29.0, p = 0.072) with the prevalence of asthma: the median concentration twice as high as compared to apartments with no reported asthma: 2.87 x 10^7 #/m^3 in apartments with asthma prevalence vs. 1.45 x 10^7 #/m^3 in apartments with no reported asthma prevalence. The overall asthma prevalence was not associated with $PM_{2.5}$ mass concentration levels (U = 42.0, p = 0.322). These results differ from the association between the measured environmental variables and the reports of asthma attacks in the past 12 months. The questionnaire did not elicit information about whether the residents developed asthma prior to or during their stay in the investigated homes, making it more difficult to connect asthma prevalence data with our-measured environmental and building variables.

4. Discussion

4.1 Missing insulation and particles

This pilot-level study explored the potential to integrate infrared thermography with laser scanning, IAQ measurements, and resident interviews in order to provide a more comprehensive and faster assessment of building structural conditions and relate them to indoor environmental parameters and residents' well-being, such as asthma episodes in the past 12 months. Among the investigated building parameters shown in SI Table 1, missing exterior wall insulation showed a significant positive association with the concentration of airborne ultrafine particles as well as the indoor/outdoor (I/O) ratio of those particles: apartments with higher levels of missing insulation had higher number concentrations of ultrafine particles as well as higher I/O ratios. These findings suggest that missing insulation is conducive for ultrafine particle penetration and accumulation from outdoors to indoors. The observed missing insulation could be due to poor workmanship during its installation or renovation, or due to settling. Depending on the proportion of missing wall insulation, a temperature gradient can be formed between indoor and outdoor spaces leading to tangential air flow, thus creating multiple air entry zones. These zones reduce the thermal resistance of the building and could potentially facilitate particle exchange between outdoors and indoors (Silberstein et al. 1991). While particle measurements in each apartment were performed for only up to 60 min, it appears the time was sufficient to show a positive association between the number concentration of ultrafine particles and missing wall insulation. The association between the missing insulation and the presence of particles was not observed for particles larger than 300 nm, most likely because larger particles have lower penetration efficiency through the building envelope (Liu and Nazaroff 2001; Mosley et al. 2001). A limitation here is the absence of information on outdoor PM sources nearby and apartment orientation as well as prevailing wind direction as that could influence particle penetration.

It is important to point out that occupant behavior played a major role in the observed relationship between the missing insulation and the presence of ultrafine particles. The relationship described above held in apartments with no or relatively low presence of influential combustion sources, such as smoking and burning of candles or incense. On the other hand, in the apartments where such combustion sources were prevalent, the particles generated indoors overwhelmed the contribution of particles from outdoors, and no relationship between the missing insulation and particle presence was observed.

4.2 Indoor combustion sources and particle presence

As mentioned above, smoking, burning of incense or candles by the occupants played a major role in particle presence in the apartments. A study conducted in Sweden and Denmark showed an I/O of ultrafine particle number concentration comparable to our study and also demonstrated the increase in particle concentration when there were strong indoor sources such as smoking, candle burning and cooking (Matson 2005). However, different from that study we did not find an association between the frequency of cooking and the presence of ultrafine particles. Other studies have also shown a significant increase in ultrafine particle presence indoors due to smoking (Alderman and Ingebrethsen 2011; Valente et al. 2007; Wallace and Ott 2011) and burning of candles or incense (Géhin et al. 2008; Vinzents et al. 2005) .

We found that 65% of the study's participants had children younger than 12 years and that 67% of smokers had children living with them. The smoking-related particles not only degrade indoor air quality but can also cause developmental issues in children (Klepeis et al. 2017). The residents and their families are exposed to smoking-generated particles not only via first-hand and second-hand smoking but also due to resuspension of deposited smoke-related particles. Resuspension of floor-deposited dust would especially elevate exposures of children due to the proximity of their breathing zones to the floor (Burtscher and Schüepp 2012). The resuspension of deposited particles depends on their size (Qian et al. 2014; Qian and Ferro 2008), while the size of smoking-originated particles depends on the nicotine content and the nicotine delivery device, e.g., cigarette manufacturing technology (Becquemin et al. 2007), e-cigarettes (Glantz and Bareham 2018) , cigars (Baker et al. 2000), or water pipes (Akl et al. 2010). However, our questionnaire did not inquire about the type of smoking, and we cannot speculate about the size of produced particles and how that would affect particle lung deposition of the exposed residents.

In the absence of smoking and/or burning of candles or incense, the number concentration of ultrafine particles was significantly higher in the “high” missing insulation group compared to the “low” missing insulation group, thus increasing personal exposure to ultrafine particles. We speculate that this increase in particle concentration indoors was due to their penetration from outdoors. For example, a study by Zhu et al. (2005) described the penetration of ultrafine particles (6 – 220 nm) into urban residences located near a freeway. Infiltration of ultrafine particles through the building envelope was reported to be highest for particles in size range of 70 to 100 nm in residences with no known indoor aerosol sources, which is in agreement with our study.

4.3 Missing insulation, particle concentration, and apartment location

Apartments with the higher levels of missing insulation seemed to be mostly corner apartments; concurrently, the corner apartments also had a substantially and significantly higher number concentration of ultrafine particles. Smoking did not seem to affect the ultrafine particle presence in corner apartments as an equal number of smokers and non-smokers lived in corner apartments. The corner apartments were also associated with a lower resistance to heat flow as measured by the R-value, which, in turn, could lead to lower insulating properties of the apartments (US DOE, n.d.). Silberstein et al. (1991) described air infiltration through air entry zones, due to external wind velocity and its orientation, as a factor for the reduction of thermal resistance.

4.4 Missing insulation, particle concentration, and asthma

Since the observed concentrations of airborne particles had a significant correlation with the residents’ reports of recent asthma episodes, one can conclude that building deficiencies such as missing insulation play a role in residents’ well-being. Ultrafine particles are particularly important because of their high surface area and high potential to absorb toxic air pollutants per unit mass (Delfino et al. 2005; Sioutas et al. 2005; Sultan et al. 2011). A randomized clinical trial study reported the impairment of alveolar gas exchange and mild small-airways dysfunction in healthy adults when exposed to ultrafine carbon particles (diameter less than 100 nm) (Pietropaoli et al. 2004). Subjects with asthma were reported to have a higher lung fractional deposition during exercising compared to healthy subjects when exposed to ultrafine carbon particles (Chalupa et al. 2004). Penttinen et al. (2001) reported an association between particles 10 nm-1 µm and poor respiratory health measured by self-monitored peak expiratory flow rate in adult nonsmoking asthmatics. A recent study conducted with nonsmoking asthmatics showed an increase in acute systemic inflammation following exposure to airport-related ultrafine particles (Habre et al. 2018). A cross-sectional study of 655 children attending an elementary school in Australia showed a positive association between ultrafine particles and systemic inflammation but did not observe measurable respiratory symptoms (Clifford et al. 2018). Hence, evaluation of exposures of asthmatics to ultrafine particles in locations without combustion activities could be an important parameter in overall health evaluation.

Our study also found a positive association between $PM_{2.5}$ mass concentrations in apartments and reported asthma cases even though measurements were taken only once. A similar result was reported between asthma and other respiratory diseases in children younger than 15 years and an increase in asthma hospital admissions when exposed to increasing concentrations of both fine and coarse PM (Tecer et al. 2008).

While we showed an association between the airborne particle presence and recent occurrence of asthma, our information on asthma was based entirely on residents' responses. We also did not get information whether any medications were used. In addition, the number of participants was low. Thus, our findings should be verified in a larger study investigating IAQ and health.

5. Conclusions

This pilot field study showed that the proposed method of using multiple data streams, e.g., infrared thermography with laser scanning, indoor air quality measurements, and questionnaires, can generate a more comprehensive building assessment and its effect on IAQ and the impact on residents' health than would be possible with just one separate data stream. At the same time, we recognize that the study evaluated a limited number of buildings and individual apartments. However, this pilot study demonstrates the feasibility of integrating different and sophisticated techniques into the building and its IAQ investigations. Future studies should apply and investigate this methodology on a larger scale. Also, we found that only one of the building deficiencies determined by the infrared thermography with laser scanning, i.e., missing insulation, correlated with IAQ parameters and residents' health. It is likely that larger studies will show correlations with other types of building deficiencies as well. In summary, we believe that the data obtained in this pilot study will encourage other researchers to integrate various techniques in their investigations of buildings, IAQ, and residents' health so that a more comprehensive relationship between building performance, IAQ, and residents' health can be developed.

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Conflict of Interest

The authors declare that they have no conflict of interest.

References

Akl EA, Gaddam S, Gunukula SK, Honeine R, Jaoude PA, Irani J. 2010. The effects of waterpipe tobacco smoking on health outcomes: a systematic review. Int J Epidemiol 39:834–857; doi:10.1093/ije/dyq002.

Alba MI, Barazzetti L, Scaioni M, Rosina E, Previtali M. 2011. Mapping infrared data on terrestrial laser scanning 3D models of buildings. Remote Sens 3:1847–1870; doi:10.3390/rs3091847.

Alderman SL, Ingebrethsen BJ. 2011. Characterization of mainstream cigarette smoke particle size distributions from commercial cigarettes using a DMS500 fast particulate spectrometer and smoking cycle simulator. Aerosol Sci Technol 45:1409–1421; doi:10.1080/02786826.2011.596862.

Allacci MS. 2005. Identifying environmental risk factors for asthma emergency care: a multilevel approach for ecological study. J Ambulatory Care Manage 28: 2–15.

Baker F, Ainsworth SR, Dye JT, Crammer C, Thun MJ, Hoffmann D, Repace JL, Henningfield JE, Slade J, Pinney J, Shanks T, Burns DM, Connolly GN, Shopland DR. 2000. Health risks associated with cigar smoking. JAMA 284:735–740; doi:10.1001/jama.284.6.735.

Balaras C, Argiriou A. 2002. Infrared thermography for building diagnostics. Energy Build 34:171–183; doi:10.1016/S0378-7788(01)00105-0.

Baldauf RW, Devlin RB, Gehr P, Giannelli R, Hassett-Sipple B, Jung H, Martini G, McDonald J, Sacks JD, Walker K. 2016. Ultrafine Particle Metrics and Research Considerations: Review of the 2015 UFP Workshop. Int J Environ Res Public Health 13; doi:10.3390/ijerph13111054.

Barreira E, de Freitas VP. 2007. Evaluation of building materials using infrared thermography. Constr Build Mater 21:218–224; doi:10.1016/j.conbuildmat.2005.06.049.

Becquemin MH, Bertholon JF, Attoui M, Roy F, Roy M, Dautzenberg B. 2007. Particle size in the smoke produced by six different types of cigarette. Rev Mal Respir 24: 845–852. doi:10.1016/S0761-8425(07)91386-8.

Ben-David T, Waring MS. 2018. Interplay of ventilation and filtration: Differential analysis of cost function combining energy use and indoor exposure to PM2.5 and ozone. Build Environ 128:320–335; doi:10.1016/j.buildenv.2017.10.025.

Bernstein JA, Alexis N, Bacchus H, Bernstein IL, Fritz P, Horner E, Li N, Mason S, Nel A, Oullette J, Reijula K, Reponen T, Seltzer J, Smith A, Tarlo SM. 2008. The health effects of nonindustrial indoor air pollution. J Allergy Clin Immunol 121:585–591; doi:10.1016/j.jaci.2007.10.045.

Bonnefoy XR, Braubach M, Moissonnier B, Monolbaev K, Röbbel N. 2003. Housing and health in Europe: Preliminary results of a Pan-European study. Am J Public Health 93: 1559–1563; doi:10.2105/AJPH.93.9.1559.

Burtscher H, Schüepp K. 2012. The occurrence of ultrafine particles in the specific environment of children. Paediatr Respir Rev 13:89–94; doi:10.1016/j.prrv.2011.07.004.

Chalupa DC, Morrow PE, Oberdörster G, Utell MJ, Frampton MW. 2004. Ultrafine particle deposition in subjects with asthma. Environ Health Perspect 112:879–882; doi:10.1289/ehp.6851.

Chenari B, Dias Carrilho J, Gameiro da Silva M. 2016. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. Renew Sustain Energy Rev 59:1426–1447; doi:10.1016/j.rser.2016.01.074.

Clifford S, Mazaheri M, Salimi F, Ezz WN, Yeganeh B, Low-Choy S, Walker K, Mengersen K, Marks GB, Morawska L. 2018. Effects of exposure to ambient ultrafine particles on respiratory health and systemic inflammation in children. Environ Int 114:167–180; doi:10.1016/j.envint.2018.02.019.

Craveiro F, Bàrtolo H, Duarte JP, Bàrtolo PJ. 2018. Customizing insulation material properties for building retrofitting : from infrared thermography to additive manufacturing.; doi:https://doi.org/10.25341/D4MS3F.

Dabass A, Talbott EO, Rager JR, Marsh GM, Venkat A, Holguin F, Sharma RK. 2018. Systemic inflammatory markers associated with cardiovascular disease and acute and chronic exposure to fine particulate matter air pollution (PM2.5) among US NHANES adults with metabolic syndrome. Environ Res 161:485–491; doi:10.1016/j.envres.2017.11.042.

Dales R, Liu L, Wheeler AJ, Gilbert NL. 2008. Quality of indoor residential air and health. CMAJ 179:147–152; doi:10.1503/cmaj.070359.

Dall'O' G, Sarto L, Panza A. 2013. Infrared Screening of Residential Buildings for Energy Audit Purposes: Results of a Field Test. Energies 6:3859–3878; doi:10.3390/en6083859.

Delfino RJ, Sioutas C, Malik S. 2005. Potential role of ultrafine particles in associations between airborne particle mass and cardiovascular health. Environ Health Perspect 113:934–946; doi:10.1289/ehp.7938.

DiNapoli TP. 2014. The prevalence and cost of asthma in New York State. Off N Y State Comptroller. Available: https://www.osc.state.ny.us/reports/economic/asthma_2014.pdf.

Dominici F, Peng RD, Bell ML, Pham L, McDermott A, Zeger SL, Samet JM. 2006. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. JAMA 295:1127–1134; doi:10.1001/jama.295.10.1127.

Eftim SE, Samet JM, Janes H, McDermott A, Dominici F. 2008. Fine particulate matter and mortality: A comparison of the Six Cities and American Cancer Society Cohorts with a Medicare cohort. Epidemiology 19: 209–216; doi:10.1097/EDE.0b013e3181632c09.

Erqou S, Clougherty JE, Olafiranye O, Magnani JW, Aiyer A, Tripathy S, Kinnee E, Kip KE, Reis SE. 2018. Particulate matter air pollution and racial differences in cardiovascular disease risk. Arterioscler Thromb Vasc Biol 935–942; doi:10.1161/ATVBAHA.117.310305.

FLIR System. 2011. Thermal imaging guidebook for building and renewable energy applications. Available: http://www1.flir.com/thermal-imaging-building-guidebook-au [accessed 8 June 2018].

Fokaides PA, Kalogirou SA. 2011. Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes. Appl Energy 88:4358–4365; doi:10.1016/j.apenergy.2011.05.014.

Géhin E, Ramalho O, Kirchner S. 2008. Size distribution and emission rate measurement of fine and ultrafine particle from indoor human activities. Atmos Environ 42:8341–8352; doi:10.1016/j.atmosenv.2008.07.021.

Glantz SA, Bareham DW. 2018. E-Cigarettes: use, effects on smoking, risks, and policy implications. Annu Rev Public Health 39:215–235; doi:10.1146/annurev-publhealth-040617-013757.

Gorse C, Johnston D. 2012. Thermal Bridge: Oxford Dictionary of Construction, Surveying, and Civil Engineering. 3rd ed. Oxford: Oxford UP.

Gouveia N, Junger WL. 2018. Effects of air pollution on infant and children respiratory mortality in four large Latin-American cities. Environ Pollut 232:385–391; doi:10.1016/j.envpol.2017.08.125.

Guo M. 2015. Spatially resolved infrared imaging for building performance evaluation (Master's thesis). Rutgers, The State University of New Jersey.

Habre R, Zhou H, Eckel SP, Enebish T, Fruin S, Bastain T, Rappaport E, Gilliland F. 2018. Short-term effects of airport-associated ultrafine particle exposure on lung function and inflammation in adults with asthma. Environ Int 118:48–59; doi:10.1016/j.envint.2018.05.031.

Ham Y, Golparvar-Fard M. 2013. An automated vision-based method for rapid 3D energy performance modeling of existing buildings using thermal and digital imagery. Adv Eng Inform 27:395–409; doi:10.1016/j.aei.2013.03.005.

Hansen DJ. 1993. The Work Environment: Indoor Health Hazards. CRC Press.

Healey JF. 2011. Statistics: A Tool for Social Research. 8th Edition. Cengage Learning.

Janssen NAH, Fischer P, Marra M, Ameling C, Cassee FR. 2013. Short-term effects of PM2.5, PM10 and PM2.5–10 on daily mortality in the Netherlands. Sci Total Environ 463–464:20–26; doi:10.1016/j.scitotenv.2013.05.062.

Jordán-Cuebas F, Krogmann U, Andrews CJ, Senick JA, Hewitt EL, Wener RE, Allacci MS, Plotnik D. 2018. Understanding apartment end-use water Consumption in two green residential multistory buildings. J Water Resour Plan Manag 144:04018009; doi:10.1061/(ASCE)WR.1943-5452.0000911.

Karetzky M. 1977. Asthma in the South Bronx: Clinical and epidemiologic characteristics. J Allergy Clin Immunol 60:383–390; doi:10.1016/0091-6749(77)90070-7.

Kaunelienė V, Prasauskas T, Krugly E, Stasiulaitienė I, Čiužas D, Šeduikytė L, Martuzevičius D. 2016. Indoor air quality in low energy residential buildings in Lithuania. Build Environ 108:63–72; doi:10.1016/j.buildenv.2016.08.018.

Kirimtat A, Krejcar O. 2018. A review of infrared thermography for the investigation of building envelopes: Advances and prospects. Energy Build 176:390–406; doi:10.1016/j.enbuild.2018.07.052.

Klemm RJ, Mason RM. 2000. Aerosol Research and Inhalation Epidemiological Study (ARIES): air quality and daily mortality statistical modeling--interim results. J Air Waste Manag Assoc 1995 50: 1433–1439; doi:10.1080/10473289.2000.10464188.

Klepeis NE, Bellettiere J, Hughes SC, Nguyen B, Berardi V, Liles S, Obayashi S, Hofstetter CR, Blumberg E, Hovell MF. 2017. Fine particles in homes of predominantly low-income families with children and smokers: Key physical and behavioral determinants to inform indoor-air-quality interventions. PLOS ONE 12:e0177718; doi:10.1371/journal.pone.0177718.

Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann, WH. 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Expo Sci Environ Epidemiol 11:231–252; doi:10.1038/sj.jea.7500165.

Kumar P, Fennell PS, Hayhurst AN, Britter RE. 2009. Street Versus Rooftop Level Concentrations of Fine Particles in a Cambridge Street Canyon. Bound-Layer Meteorol 131:3–18; doi:10.1007/s10546-008-9300-3.

Kumar P, Morawska L, Birmili W, Paasonen P, Hu M, Kulmala M, Harrison RM, Norford L, Britter R. 2014. Ultrafine particles in cities. Environ Int 66:1–10; doi:10.1016/j.envint.2014.01.013.

Kylili A, Fokaides PA, Christou P, Kalogirou SA. 2014. Infrared thermography (IRT) applications for building diagnostics: A review. Appl Energy 134:531–549; doi:10.1016/j.apenergy.2014.08.005.

Lawrence AJ, Khan T. 2018. Indoor air quality assessment as related to household conditions in rural houses during winter season. In: *Environmental Contaminants*. *Energy, Environment, and Sustainability*. Springer, Singapore. 221–244; doi:10.1007/978-981-10-7332-8_11.

Lee S-B, Cho H-J, Ha Y-M, Kim S-J, Chung B-J, Son WK, et al. 2017. Enhancing the durability of filtration the ultrafine aerosol by electrospun polymer filter containing quaternary ammonium moiety. Polymer 121:211–216; doi:10.1016/j.polymer.2017.06.026.

Lerma C, Barreira E, Almeida RMSF. 2018. A discussion concerning active infrared thermography in the evaluation of buildings air infiltration. Energy Build 168:56–66; doi:10.1016/j.enbuild.2018.02.050.

Liu D-L, Nazaroff WW. 2001. Modeling pollutant penetration across building envelopes. Atmos Environ 35:4451–4462; doi:10.1016/S1352-2310(01)00218-7.

Ljungberg S-A. 1996. Infrared thermography as a diagnostic tool to indicate sick-house-syndrome: a case-study. Thermosense XVIII Int Conf Therm Sens Imaging Diagn Appl 2766:32–50; doi:10.1117/12.235365.

Maantay J. 2007. Asthma and air pollution in the Bronx: Methodological and data considerations in using GIS for environmental justice and health research. Health Place 13:32–56; doi:10.1016/j.healthplace.2005.09.009.

Martins LD, Martins JA, Freitas ED, Mazzoli CR, Gonçalves FLT, Ynoue RY, Hallak R, Albuquerque TT, Andrade MF. 2010. Potential health impact of ultrafine particles under clean and polluted urban atmospheric conditions: a model-based study. Air Qual Atmosphere Health 3:29–39; doi:10.1007/s11869-009-0048-9.

Mathieu-Nolf M. 2002. Poisons in the air: a cause of chronic disease in children. J Toxicol Clin Toxicol 40: 483–491; doi:10.1081/CLT-120006751.

Matson U. 2005. Indoor and outdoor concentrations of ultrafine particles in some Scandinavian rural and urban areas. Sci Total Environ 343:169–176; doi:10.1016/j.scitotenv.2004.10.002.

Mendell MJ, Fisk WJ, Kreiss K, Levin H, Alexander D, Cain WS, Girman JR, Hines CJ, Jensen PA, Milton DK, Rexroat LP, Wallingford KM. 2002. Improving the health of workers in indoor environments: priority research needs for a national occupational research agenda. Am J Public Health 92: 1430–1440; doi:10.2105/AJPH.92.9.1430.

Mendes L, Gini MI, Biskos G, Colbeck I, Eleftheriadis K. 2018. Airborne ultrafine particles in a naturally ventilated metro station: Dominant sources and mixing state determined by particle size distribution and volatility measurements. Environ Pollut 239:82–94; doi:10.1016/j.envpol.2018.03.067.

Meng QY, Turpin BJ, Korn L, Weisel CP, Morandi M, Colome S, Zhang J, Stock T, Spektor D, Winer A, Zhang L, Lee JH, Giovanetti R, Cui W, Kwon J, Alimokhtari S, Shendell D, Jones J, Farrar C, Maberti S. 2005. Influence of ambient (outdoor) sources on residential indoor and personal $PM_{2.5}$ concentrations: Analyses of RIOPA data. J Expo Sci Environ Epidemiol 15:17–28; doi:10.1038/sj.jea.7500378.

Meola C, Carlomagno GM. 2004. Recent advances in the use of infrared thermography. Meas Sci Technol 15:R27; doi:10.1088/0957-0233/15/9/R01.

Mosley RB, Greenwell DJ, Sparks LE, Guo Z, Tucker WG, Fortmann R, Whitfield C. 2001. Penetration of ambient fine particles into the indoor environment. Aerosol Sci Technol 34:127–136; doi:10.1080/02786820117449.

Nazaroff WW. 2004. Indoor particle dynamics. Indoor Air 14:175–183; doi:10.1111/j.1600-0668.2004.00286.x.

Niu J. 2004. Some significant environmental issues in high-rise residential building design in urban areas. Energy Build 36:1259–1263; doi:10.1016/j.enbuild.2003.07.005.

Oliver LC, Shackleton BW. 1998. The indoor air we breathe. Public Health Rep Wash DC 1974 113: 398–409.

Penttinen P, Timonen KL, Tiittanen P, Mirme A, Ruuskanen J, Pekkanen J. 2001. Number concentration and size of particles in urban air: effects on spirometric lung function in adult asthmatic subjects. Environ Health Perspect 109: 319–323; doi:10.1289/ehp.01109319.

Pietropaoli AP, Frampton MW, Hyde RW, Morrow PE, Oberdörster G, Cox C, Cox C, Speers DM, Frasier LM, Chalupa DC, Huang L, Utell MJ. 2004. Pulmonary function, diffusing capacity, and inflammation in healthy and ssthmatic subjects exposed to ultrafine particles. Inhal Toxicol 16:59–72; doi:10.1080/08958370490443079.

Platts-Mills TA. 1994. How environment affects patients with allergic disease: indoor allergens and asthma. Ann Allergy 72: 381–384.

Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287:1132–1141; doi:10.1001/jama.287.9.1132.

Pope CA, Burnett RT, Thurston GD, Thun MJ, Calle EE, Krewski D, Godleski JJ. 2004. Cardiovascular mortality and long-term exposure to particulate air pollution: Epidemiological evidence of general pathophysiological pathways of disease. Circulation 109:71–77; doi:10.1161/01.CIR.0000108927.80044.7F.

Qian J, Ferro AR. 2008. Resuspension of Dust Particles in a Chamber and Associated Environmental Factors. Aerosol Sci Technol 42:566–578; doi:10.1080/02786820802220274.

Qian J, Peccia J, Ferro AR. 2014. Walking-induced particle resuspension in indoor environments. Atmos Environ 89:464–481; doi:10.1016/j.atmosenv.2014.02.035.

RESNET. 2012. RESNET interim guidelines for thermographic inspections of buildings.

Samoli E, Peng R, Ramsay T, Pipikou M, Touloumi G, Dominici F, Burnett R, Cohen A, Krewski D, Samet J, Katsouyanni K. 2008. Acute effects of ambient particulate matter on mortality in Europe and North America: results from the APHENA study. Environ Health Perspect 116:1480–1486; doi:10.1289/ehp.11345.

Schwartz J, Spix C, Touloumi G, Bachárová L, Barumamdzadeh T, le Tertre A, Piekarksi T, Ponce de Leon A, Pönkä A, Rossi G, Saez M, Schouten JP . 1996. Methodological issues in studies of air pollution and daily counts of deaths or hospital admissions. J Epidemiol Community Health 50 Suppl 1: S3-11.

Seigneur C. 2009. Current Understanding of Ultrafine Particulate Matter Emitted from Mobile Sources. J Air Waste Manag Assoc 59:3–17; doi:10.3155/1047-3289.59.1.3.

Silberstein A, Arquis E, McCaa D. 1991. Forced convection effects in fibrous thermal insulation. *Insulation Materials: Testing and Applications, 2nd Volume* (R. Graves and D. Wysocki, eds). ASTM International:100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. 292-292–18.

Sioutas C, Delfino RJ, Singh M. 2005. Exposure assessment for atmospheric ultrafine particles (UFPs) and implications in epidemiologic research. Environ Health Perspect 113:947–955; doi:10.1289/ehp.7939.

Sultan ZM, Nilsson GJ, Magee RJ. 2011. Removal of ultrafine particles in indoor air: Performance of various portable air cleaner technologies. HVACR Res 17:513–525; doi:10.1080/10789669.2011.579219.

Tecer LH, Alagha O, Karaca F, Tuncel G, Eldes N. 2008. Particulate matter (PM2.5, PM10-2.5, and PM10) and children's hospital admissions for asthma and respiratory diseases: a bidirectional case-crossover study. J Toxicol Environ Health A 71:512–520; doi:10.1080/15287390801907459.

Tobías A, Rivas I, Reche C, Alastuey A, Rodríguez S, Fernández-Camacho R, Sánchez de la Campa AM, de la Rosa J, Sunyer J, Querol X. 2018. Short-term effects of ultrafine particles on daily mortality by primary vehicle exhaust versus secondary origin in three Spanish cities. Environ Int 111:144–151; doi:10.1016/j.envint.2017.11.015.

US DOE. Insulation. Available: https://www.energy.gov/energysaver/weatherize/insulation [accessed 13 August 2018].

US EPA. 2014. NAAQS Table. US EPA. Available: https://www.epa.gov/criteria-air-pollutants/naaqs-table [accessed 6 June 2018].

USEPA. 2003. A standardized EPA protocol for characterizing indoor air quality in large office buildings, Indoor Air Division, Washington D.C. and Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, NC.

Valente P, Forastiere F, Bacosi A, Cattani G, Carlo SD, Ferri M, Figà-Talamanca I, Marconi A, Paoletti L, Perucci C, Zuccaro P. 2007. Exposure to fine and ultrafine particles from secondhand smoke in public places before and after the smoking ban, Italy 2005. Tob Control 16:312–317; doi:10.1136/tc.2006.019646.

Vinzents PS, Møller P, Sørensen M, Knudsen LE, Hertel O, Jensen FP, Schibye B, Loft S. 2005. Personal exposure to ultrafine particles and oxidative DNA damage. Environ Health Perspect 113:1485–1490; doi:10.1289/ehp.7562.

Wallace L, Ott W. 2011. Personal exposure to ultrafine particles. J Expo Sci Environ Epidemiol 21:20–30; doi:10.1038/jes.2009.59.

Wang Q, Wang J, He MZ, Kinney PL, Li T. 2018a. A county-level estimate of PM2.5 related chronic mortality risk in China based on multi-model exposure data. Environ Int 110:105–112; doi:10.1016/j.envint.2017.10.015.

Wang Z, Calderón L, Patton AP, Allacci MS, Senick J, Wener R, Clinton JA, Gediminas M. 2016. Comparison of real-time instruments and gravimetric method when measuring particulate matter in a residential building. J Air Waste Manag Assoc 66:1109–1120; doi:10.1080/10962247.2016.1201022.

Wang Z, Xue Q, Ji Y, Yu Z. 2018b. Indoor environment quality in a low-energy residential building in winter in Harbin. Build Environ 135:194–201; doi:10.1016/j.buildenv.2018.03.012.

Wargocki P, Sundell J, Bischof W, Brundrett G, Fanger PO, Gyntelberg F, Hanssen SO, Harrison P, Pickering A, Seppänen O, Wouters P. 2002. Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN). Indoor Air 12:113–128; doi:10.1034/j.1600-0668.2002.01145.x.

Warman K, Silver EJ, Wood PR. 2009. Modifiable risk factors for asthma morbidity in bronx versus other inner-city children. J Asthma Off J Assoc Care Asthma 46:995–1000; doi:10.3109/02770900903350481.

Weich S, Blanchard M, Prince M, Burton E, Erens B, Sproston K. 2002. Mental health and the built environment: cross-sectional survey of individual and contextual risk factors for depression. Br J Psychiatry J Ment Sci 180: 428–433; doi:10.1192/bjp.180.5.428.

Wong NH, Huang B. 2004. Comparative study of the indoor air quality of naturally ventilated and air-conditioned bedrooms of residential buildings in Singapore. Build Environ 39:1115–1123; doi:10.1016/j.buildenv.2004.01.024.

Xu T, Hou J, Cheng J, Zhang R, Yin W, Huang C, Zhu X, Chen W, Yuan J. 2018. Estimated individual inhaled dose of fine particles and indicators of lung function: A pilot study among Chinese young adults. Environ Pollut 235:505–513; doi:10.1016/j.envpol.2017.12.074.

Zhou X, Cai J, zhao Y, Chen R, Wang C, Zhao A, Yang C, Li H, Liu S, Cao J, Kan H, Xu H. 2018. Estimation of residential fine particulate matter infiltration in Shanghai, China. Environ Pollut 233:494–500; doi:10.1016/j.envpol.2017.10.054.

Zhu Y, Hinds WC, Krudysz M, Kuhn T, Froines J, Sioutas C. 2005. Penetration of freeway ultrafine particles into indoor environments. J Aerosol Sci 36:303–322; doi:10.1016/j.jaerosci.2004.09.007.