Evaluating Summertime Overheating in Multi-Unit Residential Buildings Using Surveys and In-Suite Monitoring

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ABSTRACT

Multi-unit residential buildings (MURBs) are an important source of housing in many urban regions including Toronto, Canada, where MURBs provide over half of the city's housing. Many of these MURBs were constructed following the second world war (Touchie et al. 2013) and are in need of renewal to address energy performance and indoor environmental quality (IEQ) concerns. The Toronto Atmospheric Fund (TAF), a nonprofit corporation whose mandate is to reduce greenhouse gas emissions in the City of Toronto, and a local social housing provider have partnered to improve the performance of seven post-war MURBs through retrofits. To help prioritize retrofit options and assess IEQ, a monitoring program including pre-retrofit resident surveys and in-suite monitoring was implemented. The resident surveys included questions about basic demographics, resident behavior, and perceptions about IEQ. To supplement the surveys, temperature, relative humidity, and mean radiant temperature were monitored for one year in 65 suites. This paper examines the findings from both the in-suite monitoring and the resident surveys to determine the IEQ issues that should be addressed during the retrofit process. The analysis presented focuses on the summertime condition, which is of particular concern given the vulnerable populations housed in these buildings and the lack of central cooling facilities. The findings suggest that an air temperature threshold may be insufficient to ensure thermal comfort given the range of survey responses associated with the observed suite temperatures. Based on the data collected, it was not possible to explain the differences between the survey responses related to thermal comfort and the monitored conditions. Factors such as air speed, exposure to solar gains, and resident perceptions may contribute to these differences. The paper concludes with a discussion of some insights from the comparison between the survey and monitoring data and how they best can be used to inform the design of future retrofits and monitoring programs.

BACKGROUND

Southern Ontario contains almost 2000 post-war multi-unit residential buildings (MURBs) built between 1945 and 1984 that house nearly one million people (ERA Architects et al. 2010). This region contains more post-war MURBs than high-rise buildings of any type (12 stories or greater) in any other city in North America except New York City (ERA Architects 2010). Therefore, the environmental impact of these buildings is significant: in the City of Toronto alone, the entire MURB sector, including buildings constructed since 1984, is responsible for over 2.5 million tonnes eCO_2 of emissions every year (Touchie et al. 2013). These MURBs exhibit relatively high average energy use intensities between 290–330 ekWh/m^2, while some of the worst performers consume over 400 ekWh/m^2 (ERA Architects 2010; Touchie et al. 2013). As many of these towers were constructed in the post-war era, they are in need of renewal across a variety of building components including energy-related systems, creating an opportunity for major performance improvements.

In addition to having considerable energy and carbon emission implications, many of these high-rise apartment towers experience thermal comfort (IEQ) issues. In particular, comfort issues include chronic overheating, lack of temperature control at the suite level, and localized areas of high

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humidity in the kitchens and bathrooms. Although there has been extensive research on thermal comfort in commercial buildings and other workplace environments, less is known about the residential indoor environment, particularly in the multi-unit residential sector. This work aims to address this gap.

As North Americans spend more than 65% of their time in residential buildings (Klepeis et al. 2001; Leech et al. 2002), this building type can have a significant impact on occupants. A strong correlation has been found between areas of high social need in Southern Ontario and multi-residential tower neighborhoods (ERA Architects 2010). Many social housing MURB residents experience mobility and health issues and are particularly vulnerable to the quality of the indoor environment, including thermal comfort. Through energy retrofits there is an opportunity to enhance occupant comfort and health, in addition to reducing operating costs and energy consumption. However, prior to designing and implementing retrofits, it is important to understand the existing thermal comfort issues and the associated causes so they can be directly addressed by the retrofit. To gather this information, resident surveys and in-suite monitoring were used.

Occupant surveys have been used extensively to assess employee satisfaction with workplace indoor environmental quality (CBE 2004); however, use of surveys in the residential market has been less common. One survey of residential buildings in Hong Kong found that thermal comfort was considered the most important IEQ attribute by the vast majority of respondents (Lai and Yik 2009).

Previous work has shown that residents value and exercise control over their interior environment. A Toronto-based study using surveys and submetered energy data found that the majority of the variability of energy use for heating (57%) and cooling (84%) in buildings with in-suite controls was linked to occupant behavior and demographics, not the physical characteristics of the building (Brown et al. 2015). A Danish study, with a survey of over 2400 households in a variety of residential building types, found that residents highly valued the ability to open windows, even if they had mechanical ventilation (Frontczak 2012). And an Israeli study that collected short-term measurements of air and globe temperatures, relative humidity, and air speed while conducting resident surveys found that survey responses indicated that the conditions associated with satisfaction with the thermal environment varied depending on the residents' ability to control those conditions (Becker and Paciuk 2009). For example, the air temperatures considered comfortable in suites without active cooling were higher than those with cooling. At present, the residents in the seven study buildings do not have control over their heating system and lack access to central cooling, although about half of the monitored suites contain A/C units.

There have been a number of studies monitoring the indoor environment of schools and office buildings. However, this work has largely focused on evaluating ventilation levels and a variety of air quality indicators such as volatile organic compounds and particulate matter, to name a few, rather than thermal comfort and extreme temperatures. A school in Munich that was monitored to evaluate the thermal comfort found that night ventilation was able to reduce maximum daytime temperatures in the classrooms and improve thermal comfort (Wang et al. 2015).

Other studies have combined occupant survey data with monitoring data. A three-year study of 12 low-energy office buildings in Germany evaluated thermal comfort through occupant surveys and indoor temperature monitoring and found that 41% of occupants were dissatisfied with temperature in the summer compared to only 24% in the winter, even though indoor temperature and humidity levels were similar between the two seasons (Pfafferott et al. 2007). The authors concluded that lower occupant satisfaction cannot be explained by room temperature only. The study also found that extreme summer temperatures in 2003 made it difficult for buildings without active cooling controls to maintain a comfortable environment. A similar study in Germany found that occupant thermal comfort in the workplace correlates poorly with indoor temperature (Wagner and Gossauer 2007). One Californian study of 16 apartments in three buildings, which served a low-income population, monitored a number of IEQ parameters, including temperature and relative humidity. The monitoring was conducted over two one-week periods before and after energy retrofits that were also intended to improve IEQ (Noris et al. 2013). The researchers found improved post-retrofit thermal comfort based on a calculated comfort zone. They also conducted a survey but did not indicate how the thermal comfort responses compared to the measured data.

To the authors' knowledge there are no studies that combine the use of continuous long-term in-suite monitoring of thermal comfort parameters with resident comfort surveys in the MURB sector. This study addresses this gap to explore the correlation between actual comfort data and comfort perceived by the occupants, among other objectives.

OBJECTIVES

Data collected through surveys and in-suite monitoring were used to assess resident comfort, among other things, and inform the retrofit design process of seven multi-residential buildings. By using these data to determine the most significant IEQ issues, retrofit measures can be prioritized. Overall, these data provide new information about the quality of the indoor environment in post-war MURBs used for social housing and establish the need for IEQ improvements as part of building energy retrofits.

A round table led by Toronto's Public Health department in March 2015 identified the health impacts of extreme heat in MURBs and the building operational challenges that influence the residents' ability to stay cool during summer months (Campbell 2015). In a recent report, Toronto Public Health indicated that by 2049, the city will experience an additional 46 days with exterior temperatures exceeding 30°C (Meaney and Jackson 2015). A similar trend is expected in urban regions across North America in the coming decades (Kahn 2015). With a projected increase in days where the exterior temperature will exceed 30°C, an assessment of current comfort conditions is necessary to develop strategies for dealing with extreme temperatures in the future. Of particular concern are populations most vulnerable to extreme heat, such as residents of social housing, many of whom live in post-war MURBs. As such, this paper presents an analysis of the survey and monitoring data to assess summertime thermal comfort in 65 suites across seven post-war MURBs. The following objectives, presented in order of importance, were used to guide the analysis:

1. Determine when overheating occurs and how widespread this issue is across the seven buildings and, if possible, what factors drive the prevalence of these conditions.
2. Determine if the resident survey responses correlate well to the monitored data and whether they can provide sufficient indication of the existence of summertime thermal comfort issues (i.e., can surveys be used in lieu of in-suite monitoring to reliably identify overheating?)
3. Use data to prioritize the thermal comfort issues that need to be addressed during the building retrofits.

METHODOLOGY

The study involved collection of data from resident surveys and in-suite monitoring prior to the retrofit of seven social housing MURBs owned by the local social housing provider. Table 1 summarizes the basic characteristics of the seven buildings in the study as well as the number of suites surveyed and monitored in each building.

All seven buildings are heated through perimeter hydronic baseboards without any in-suite thermostats or controls. There is no central cooling or ceiling-mounted fans in the suites, but 47% of the monitored suites have free-standing or window-mounted air conditioning (A/C) units. Some residents also have free-standing fans. Fresh air is provided through a pressurized corridor ventilation system. Fresh air supply rates measured at the rooftop intake were 45%–50% below the ASHRAE Standard 62.1 requirements of 14,000–27,000 cfm, depending on the building size (ASHRAE 2013b). Buildings A–E have central bathroom exhaust fans, while Buildings F and G exhaust bathroom air direct to the exterior through the wall of each suite. Only Building D has kitchen exhaust to the exterior. Units at the other buildings have either a recirculating range hood or no form of kitchen exhaust. Rooftop exhaust flow rates measured in Buildings A and B were 25% below the 9200 cfm code requirements. In-suite exhaust flow rates measured in 31 suites across Buildings A–E were 25%–65% below the 25–50 cfm code requirements (ASHRAE 2013b).

In Buildings A–B and F–G, each glazing unit consists of a fixed single-glazed unit over two layers of single-glazed double sliders, as shown in Figure 1. Buildings C–E have the same configuration with an additional set of single-glazed double sliders below, also shown in Figure 1. Apartments on the fourth floor at Buildings A–B have fixed double-glazed units over the sliders. The window-to-wall ratios are presented in Table 1 and representative photos of one building on each site are shown in Figure 2. Many of the suites had interior blinds or curtains, but the use of these shading devices was not monitored. The as-built drawings do not indicate a low-emissivity coating on the double-glazed units. This was verified through site observations.

There were two data collection methods used in this study: surveys of building residents and monitoring of IEQ parameters in suites using sensors. First, the survey design, suite selection, and administration of the surveys are described, followed by an outline of the monitoring program design, suite selection, and data collection.

Resident Surveys

Survey Design. The survey was designed to capture basic details about the residents, including number and age of suite occupants and behaviors such as smoking, cooking, bathing,

Table 1. Summary of Building Parameters

Bldg.	Const. Year	No. of Stories	Floor Area, ft^2	No. of Suites	No. of Suites Surveyed (% of Total)	No. of Suites Monitored (% of Total)	Type of Occupancy	Window-to-Wall Area Ratio
A	1972	4	113,580	213	30 (15%)	10 (5%)	Seniors	0.17
B	1972	4	97,920	184	25 (15%)	8 (4%)	Seniors	0.15
C	1965	7	126,540	217	33 (15%)	13 (6%)	Bachelor	0.26
D	1965	7	35,960	58	6 (10%)	3 (5%)	Seniors	0.39
E	1965	11	116,820	196	31 (16%)	9 (5%)	Bachelor	0.25
F	1974	19	148,485	165	25 (15%)	10 (7%)	Family	0.24
G	1974	18	206,928	204	30 (15%)	12 (6%)	Family	0.16

Figure 1 *Typical window configurations at (a) Buildings A–B, (b) Buildings C–E, and (c) Buildings F–G.*

Figure 2 *Photos of one representative building from each site (a) Site 1: Buildings A–B, (b) Site 2: Buildings C–E, and (c) Site 3: Buildings F–G.*

and cleaning. Residents were asked to rate thermal comfort during summer and winter as well as indicate the existence of odors or drafts and excessive moisture or dryness in the air. They were also asked about any measures they had taken to alter their interior environment such as use of heaters, air conditioners, fans, odor control, humidifiers/dehumidifiers, operation of doors and windows, and use of weatherstripping. A number of previous studies were consulted in the development of the survey questions (Bohac and Hewett 2004; Engvall et al. 2000; Frontczak 2012; CCOHS 2014; Reijula 2004). This paper is based on the results of the pre-retrofit survey. An identical survey will be conducted following completion of the retrofits in each building (estimated winter 2017), and the results will be compared to the pre-retrofit survey.

Suite Selection. The resident surveys were completed prior to installation of the monitoring equipment, so a greater number of suites were surveyed than what was required for the monitoring program. The survey was conducted in 180 suites and monitoring was done in 65 of those suites. This larger sample of surveyed suites served two purposes: to allow an additional pool of surveyed suites to draw from in the event of attrition and to capture a larger sample size than what was possible with the monitored suites. Furthermore, participants were excluded from the monitoring phase of the study if they intended to move out of their suite in the next 12–18 months.

Excluding the top and bottom floors, the highest and lowest floors in each building were targeted first, moving closer to the neutral pressure plane as the surveying proceeded. The intent with this approach was to capture survey responses in the suites likely to experience the most extreme thermal comfort conditions in summer and winter. Suites with same layout and exterior exposure were also targeted, so that they could be directly compared. This excluded corner and end suites in addition to the top and bottom floors, as mentioned. Thus, random sampling was not employed in participant recruitment.

Administration of Surveys. Prior to the start of the project, an invitation to an information session was delivered in writing to each of the suites and fliers were posted throughout the building. One information session was held on each of the three sites (each site contained two or three buildings). The survey was administered in person by a third-party research and analytics firm in January and February 2015. Administrators went door-to-door and conducted the surveys electronically using tablets that required a response to each question before moving on to the next. A script was used to deliver the survey in the same way to each resident. Compensation for any inconvenience and time associated with study participation was provided in the form of gift cards from the grocery store located closest to each building. Participants were able to withdraw from the study at any time and could keep any gift cards received to date.

Monitoring

The in-suite monitoring program was implemented to evaluate resident comfort, provide context to the survey results, and help establish the pre-retrofit baseline indoor environment.

Program Design. Sensor packages were deployed in each suite to assess various IEQ parameters. The sensor package, shown in Figure 3, included a HOBO U12 data logger with integrated air temperature and relative humidity sensors. The mean radiant temperature (MRT) sensor consisted of an external temperature probe shielded from the room by a hollow, black plastic hemisphere and was connected to the data logger through an external channel. Table 2 includes details of the sensors used. Prior to installation, all sensors were collocated for a six-hour period and the resulting data were checked to ensure the difference between the recorded values and the mean and median of all recorded values were within the accuracy of each sensor.

Figure 4 shows the approximate location of the sensor packages at Buildings F and G. Each sensor package was installed in a similar location in each suite approximately 30 cm from the ceiling on an interior wall to ensure the sensor was out of direct solar radiation for most of the day. Since the MRT sensors were not positioned in the middle of the suites, according to ASHRAE Standard 55 (ASHRAE 2013a), they are only used to compare the relative differences in MRT at the sensor location between suites rather than provide an absolute value of the MRT.

Suite Selection and Data Collection. From the group of 180 survey participants, summertime data was collected from 65 suites that were instrumented with IEQ monitoring equipment. The suites chosen for monitoring were selected based on orientation and location in each building, not random sampling methods. Ideally, groups of suites horizontally or vertically adjacent to one another were chosen to facilitate isolation of certain explanatory variables such as exposure to solar radiation

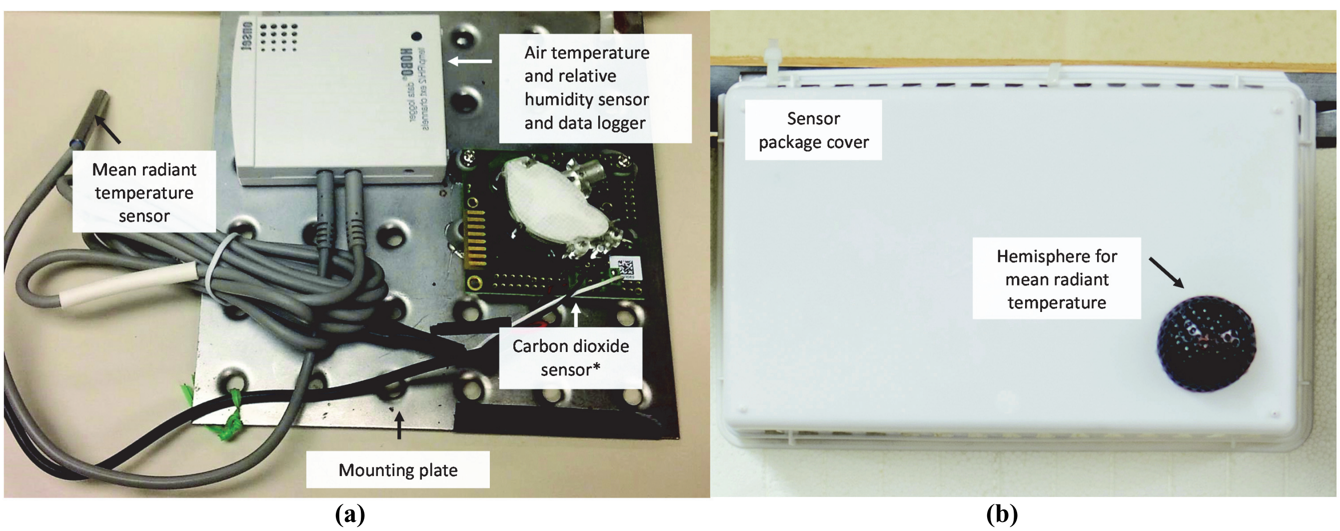


Figure 3 *(a) Sensor package components and (b) sensor package cover.*
** Data from the carbon dioxide sensors is excluded from the analysis presented in this paper.*

Table 2. Summary of Sensor Specifications

Measurement	Sensor Type	Accuracy	Accuracy Threshold
Air temperature	Onset HOBO U12-13	±0.35°C	0°C–50°C
Mean radiant temperature	Onset TMCx-HD	±0.25°C	0°C–50°C
Relative humidity	Onset HOBO U12-13	±2.5% rh	10%–90%

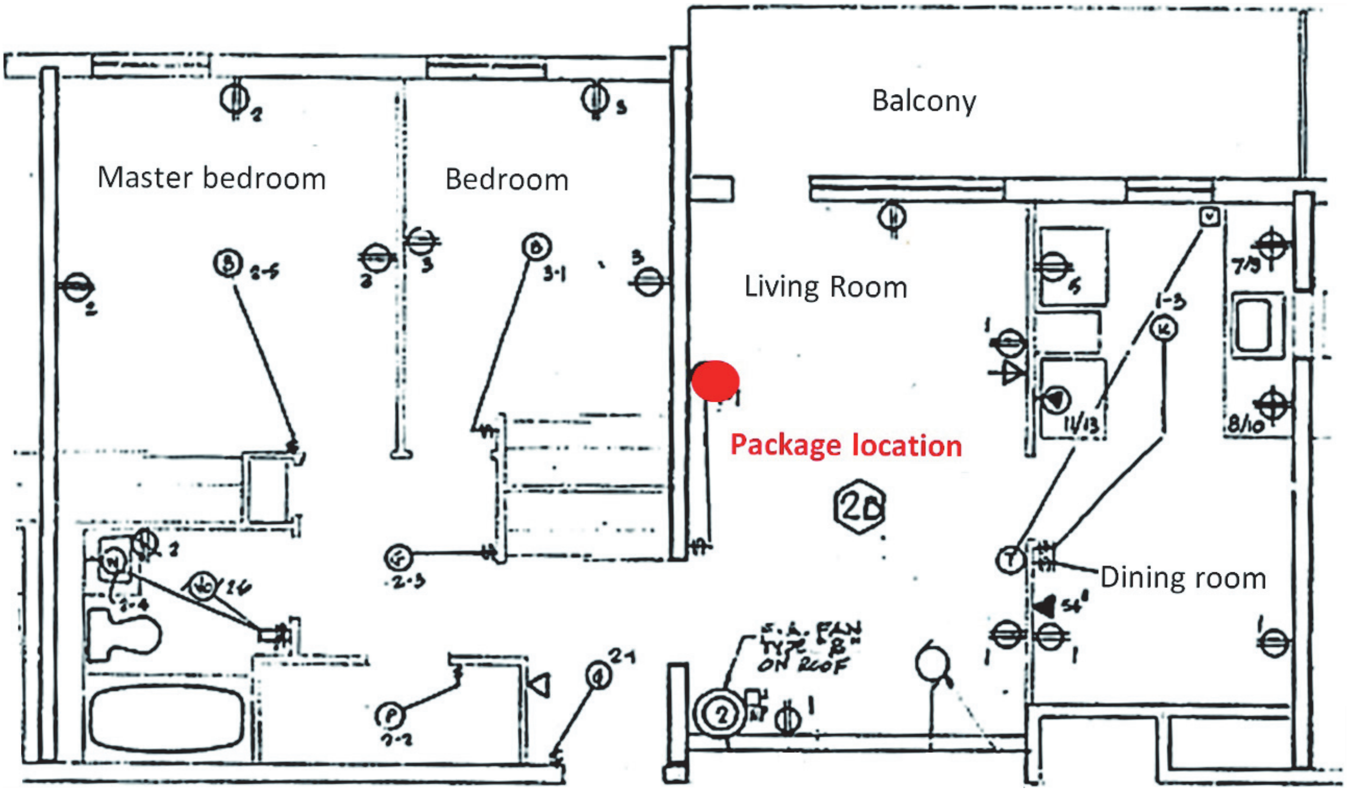


Figure 4 *Typical sensor package location—Buildings F and G.*

and the effects of stack action.The resulting selected units and a summary of window orientations are shown in Figures 5 and 6, respectively. The IEQ monitoring program is ongoing and will continue until one year after the retrofit work is completed. This paper focuses on data collected from June 1, 2015 to August 31, 2015. Measurements were recorded once every 15 minutes and data were collected from the loggers in each suite every three months. During the site visits, the presence of air conditioners and fans were noted, but the presence and use of interior blinds and curtains was not.

RESULTS AND DISCUSSION

This section begins with an overview of the survey and monitoring data separately. Then the relationship between the two data sources is investigated and the reasons for different comfort conditions are explored.

Resident Surveys

The surveys were conducted over a period of ten days between January and February 2015. Respondents were asked how comfortable they were in their apartment during the summer months and how often they used of air conditioners and fans. In addition to the surveys, the presence of air conditioners was visually verified during the monitoring period. Table 3 shows the percentage of respondents in each building who reported feeling "Too cold," "Just right," "Too warm," or "Don't know."

Just over half of the residents across all seven buildings reported feeling too warm during the summer months. However, there were large differences between the buildings. Only 32% of the respondents in Building B reported feeling "Too warm," while 77% of respondents reported feeling "Too warm" in Building G. To explore the physical causes of this difference, the percentage of residents reporting "Too warm" conditions were plotted against building height in Figure 7.

The strong correlation here suggests a relationship between building height and summertime discomfort. However, when the responses were distributed along the height of the building, there was no clear trend of greater thermal discomfort near the top of the building, as perhaps expected due to stack effect. Instead, the "Too warm" responses are distributed throughout the building. This suggests that other factors are impacting perceived thermal comfort such as solar radiation, air movement, and/or resident behaviors and preferences.

A detailed shadow study is beyond the scope of this paper, but examination of the building orientations, shown in Figure 5, and site observations during the summer were used to explain some of the differences between the buildings. In Figure 5, the buildings sizes and the separation between buildings on Sites 1 and 2 are to scale relative to one another, while the buildings on Site 3 are further apart than they appear. The number of suites monitored and their approximate location in each building are shown on the floor plans. Where the

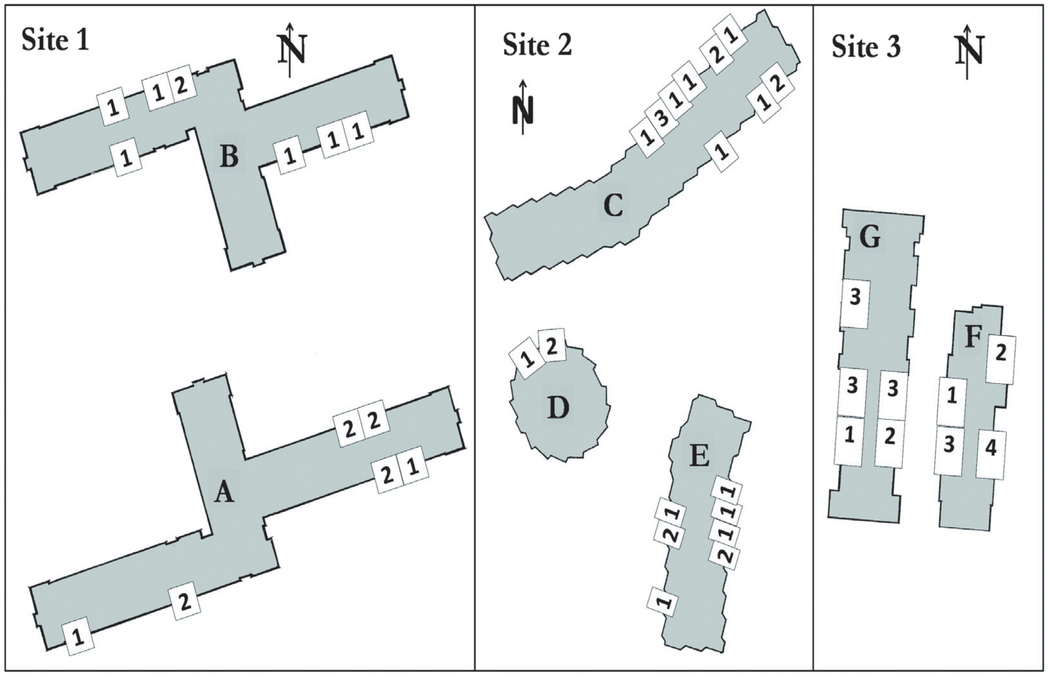


Figure 5 *Location and number of suites monitored at each site.*

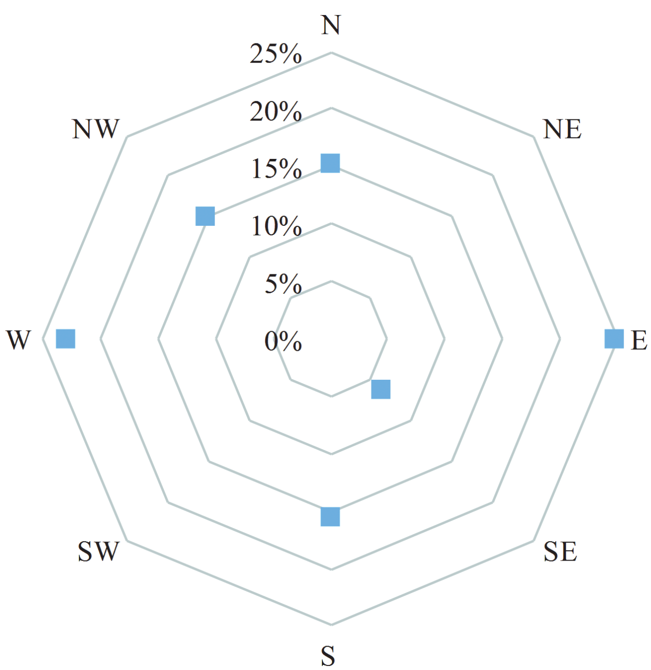


Figure 6 *Window orientations by percentage of total number of monitored suites.*

numbers are greater than 1, the monitored suites are located directly above and below one another. Figure 6 shows the glazing orientation, expressed as a percentage of the total number of monitored units.

When comparing buildings on the same site, the differences in satisfaction with thermal comfort may relate to the impact of shading from nearby trees and buildings. For example, greater levels of perceived comfort in Buildings A and B could be a result of trees shading the South side of each building and the fact that no suites facing East or West were monitored. Similarly, Building G shades Building F in the late afternoon and early evening, which might contribute to the slightly higher comfort reported by the residents in Building F. Buildings C and E are interesting in that Building C has North and South exposure while Building E has East and West exposure, which means different parts of each building will see solar radiation at different times of the day. This will be explored further using the monitored temperature data below. Another explanation for varied levels of thermal comfort could be the use of interior blinds and curtains. However, resident use of interior shading devices was not monitored or assessed through the surveys, so it is not possible to test this theory.

The survey data also showed how often residents used a fan and/or air conditioner in their suites. Figure 8 shows how this equipment use varies with the perceived summertime comfort. Residents who said they were "Too warm" during the summer months and did not have access to a fan and/or A/C represented 13% and 14% of total respondents, respectively. Fans and/or A/C units were used daily by 18% (fans) and 19% (A/C) of respondents who considered conditions "Too warm". Only 5% (fans) and 7% (A/C) of respondents who considered conditions "Just right" used this equipment daily.

Table 3. Survey Responses Related to Thermal Comfort

Building	A	B	C	D	E	F	G	Total
Too cold	0%	0%	3%	0%	3%	4%	0%	2%
Just right	53%	68%	45%	67%	39%	20%	10%	40%
Too warm	47%	32%	48%	33%	52%	72%	77%	54%
Don't know	0%	0%	3%	0%	6%	4%	13%	4%
Number of respondents	30	25	33	6	31	25	30	180

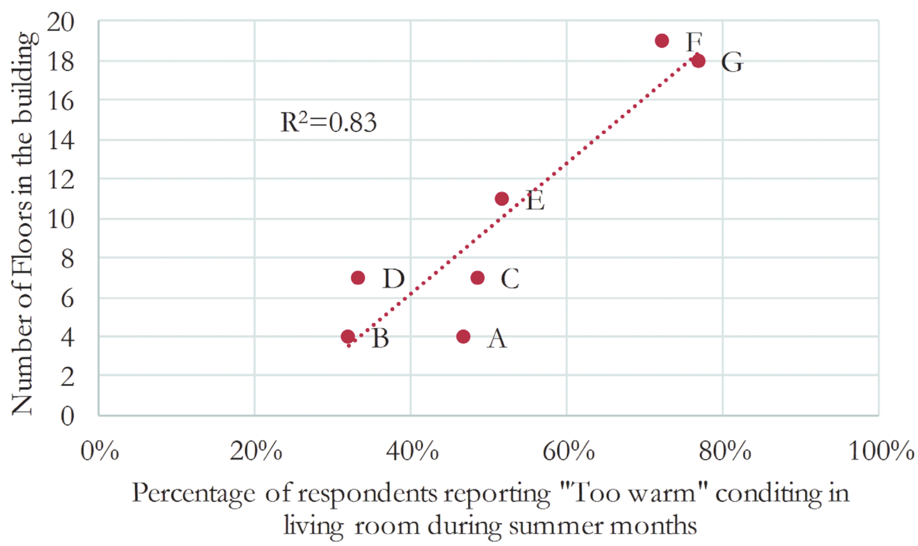


Figure 7 *Influence of building height on percentage of respondents reporting "Too warm" conditions.*

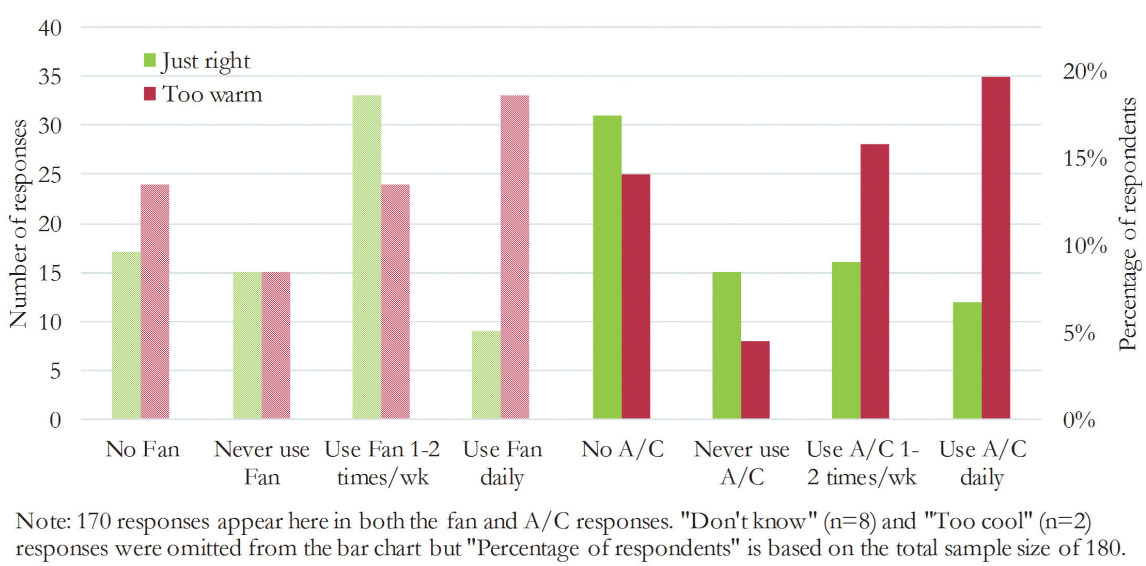


Figure 8 *Thermal comfort survey response and reported use of cooling controls.*

The survey did not include questions about whether residents chose to use fans and/or A/Cs to maintain “Just right” conditions or whether they did not need to use this equipment because the conditions were “Just right”. However, the greater daily use of both fans and A/Cs by respondents who were “Too warm” suggests that, despite these temperature control measures, they were unable to achieve comfortable conditions in their suites. Fan and A/C use was also examined by building in an attempt to explain the differences in perceived comfort between the buildings, as shown in Figure 9.

Figure 9 shows the greater prevalence of fan use in Buildings A and B. This would contribute to improved thermal comfort due to greater air movement in the suite and may be one of the reasons for fewer complaints of “Too warm” conditions. A/C use was most prevalent in Buildings F and G, which also had the greatest numbers of residents reporting conditions were “Too warm.” This suggests that A/C as a temperature control mechanism was relatively ineffective in these buildings despite reported widespread use. Air leakage paths around the air-conditioner units driven by pressure differentials can potentially allow the cool, conditioned air to escape towards the exterior. Site observations have confirmed that many A/C units are not adequately installed, which could result in reducing the A/C effectiveness in cooling the units.

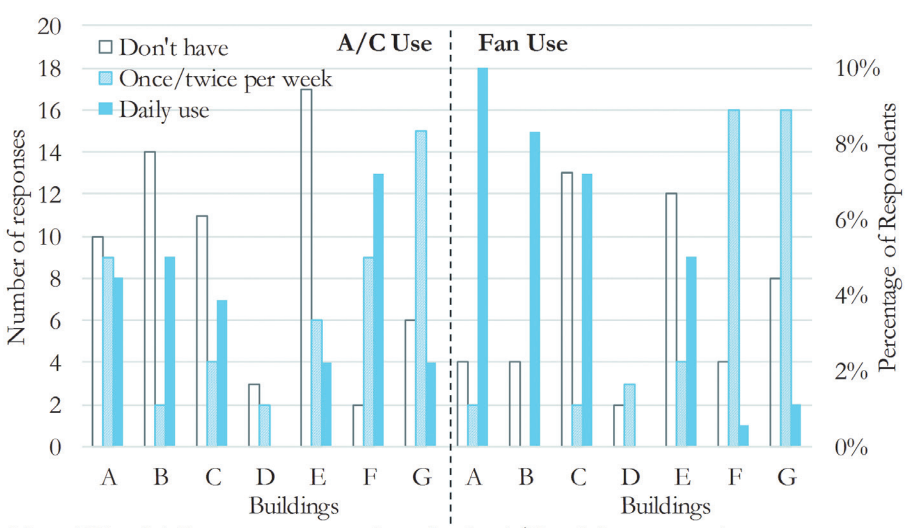
Monitoring

The monitoring included collection of air temperature, approximate mean radiant temperature, and relative humidity data in 15-minute intervals. The air temperature data is presented in this section and the MRT and relative humidity data are incorporated into the development of comfort zones when the monitoring and survey data are compared.

Analysis of the indoor air temperatures in the seven buildings revealed chronic overheating throughout the summer. Based on all of the monitored suites, the average air temperature was 27.7°C, while maximum recorded temperatures exceeded 34°C. During heat alerts issued by the City, approximately 80% of the suites surpassed 30°C during the day. Figures 10 through 12 show the percent of time suites exceeded 26°C or 28°C during the summer, by building. Suites with air conditioners are excluded from these graphs. Building D was not plotted because only three suites were monitored. A 26°C threshold was examined initially because this temperature is being explored as a maximum upper limit for rental MURBs. However, because the suites on Site 1 and Site 3 spent so much time above this 26°C threshold, the percentage of time above 28°C was used for a more meaningful comparison.

A sensitivity analysis revealed that the all suites exceeded 24°C for 100% of the time during the summer. Buildings A and B exceeded a 30°C threshold for approximately 20% of the time. In comparison, the rest of the buildings in the study rarely reached 30°C.

With the exception of a few outliers, nearly 100% of the suites in Buildings A and B were above 26°C the entire summer. Figure 10 shows that suites were over 28°C between 70% –90% of the time in June and July. The greater variation in Building A may be a result of the localized impact of shading from the surrounding trees. Despite these high air temperatures, the residents in Buildings A and B were also the most satisfied with 53% and 68%, respectively, reporting conditions were “Just right” during summer months, as shown in Table 3.



Note: 155 and 148 responses appear here for the A/C and fan use questions, respectively. "Never use" (n=25 and 31, respectively) and "Don't know" (n=0 for both) responses were omitted from the chart. "Percentage of respondents" is based on the total sample size of 180 respondents.

Figure 9 *Reported A/C and fan use.*

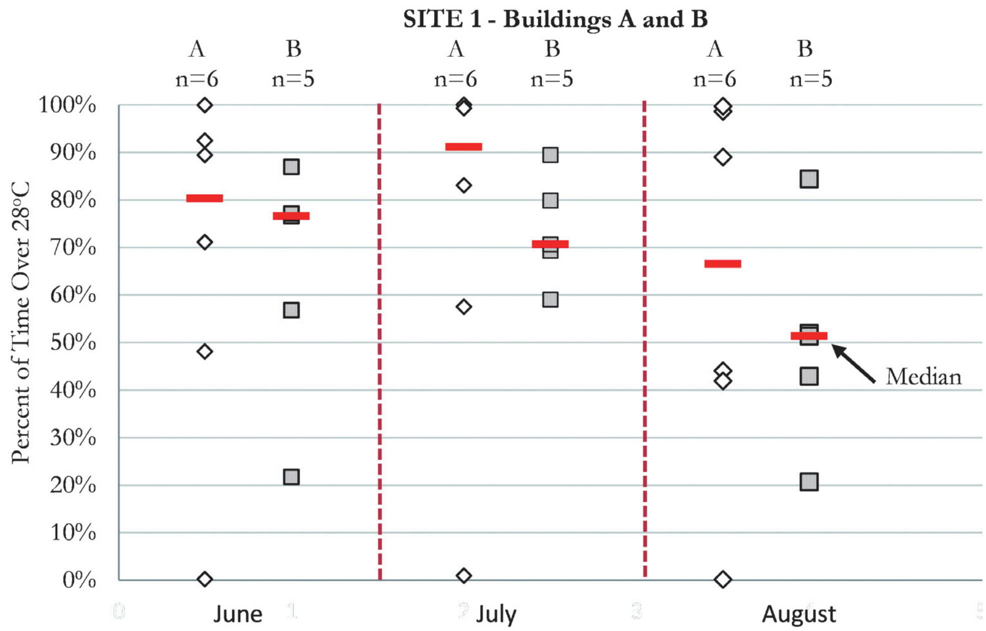


Figure 10 *Percentage of time suites at Site 1 are above 28°C.*

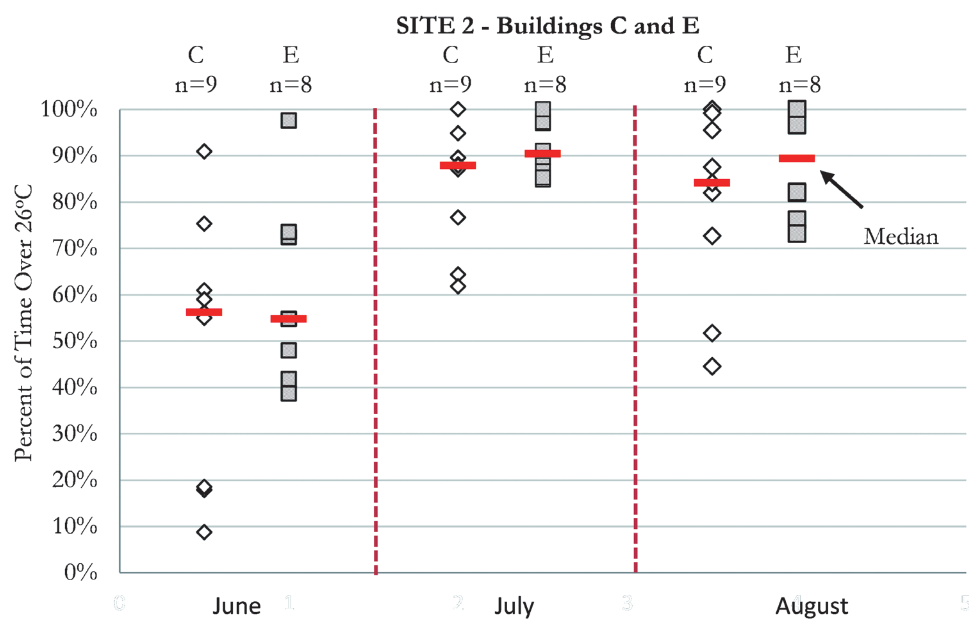


Figure 11 *Percentage of time suites at Site 2 are above 26°C.*

This may be due to the prevalence of daily fan use, shown in Figure 9, or other reasons that could not be verified with the data collected in this study, including less exposure to solar radiation or differences in resident preferences. It is interesting to note that Buildings A and B had the smallest operable glazing areas, compared to the rest of the buildings in the study. One review paper reported that seniors are less sensitive and take more time to respond to extreme heat exposure, despite being severely affected by it (Kenny et al. 2010). A telephone survey in New York City found that, while almost 80% of the seniors who participated had A/Cs, the majority did not use them for various reasons (Lane et al. 2014). Some also noted a preference for fans over A/C, did not feel the heat, or said they were used to the heat. Research has also indicated that seniors often underreport pain because they believe it is part of the normal aging process or in many cases deny it

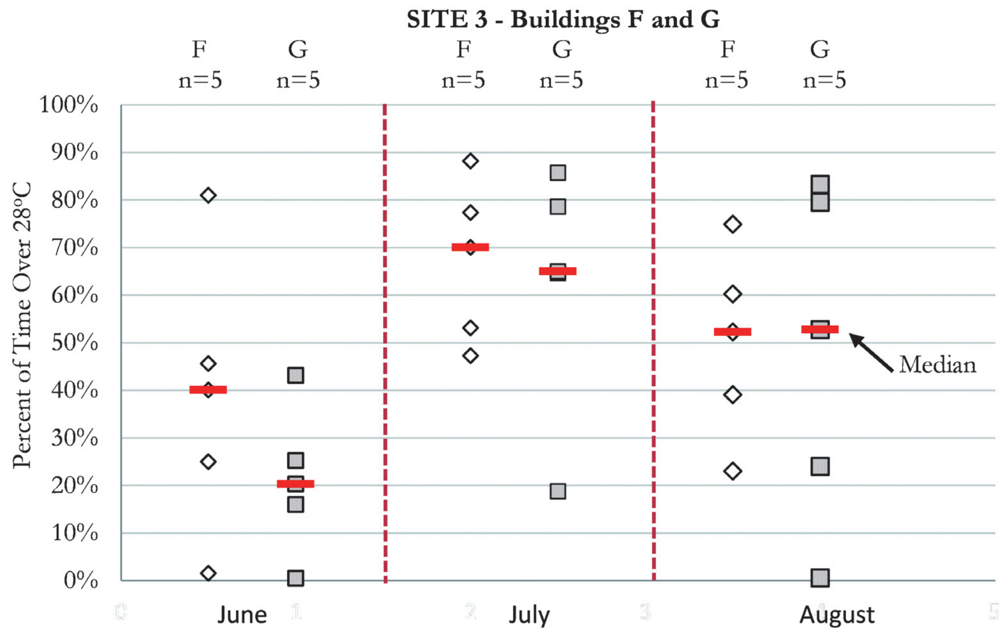


***Figure 12** Percentage of time suites at Site 3 are above 28°C.*

because they do not want to be a nuisance (Kaye et al. 2010; Ferrell et al. 2010; Herr and Mobily 1997). These studies indicate that discomfort due to overheating could similarly be underreported by senior residents.

Buildings C and E spent the least amount of time above 26°C. The temperature difference between these buildings, as shown in Figure 11, could be related to their orientation. Building E has suites facing East/West while Building C is oriented with suites facing North/South. However, it is unclear why these buildings are cooler than the other two sites, especially given the limited use of A/Cs as shown in Figure 9.

Larger temperature differences were observed between Buildings F and G, particularly in June when the suites in Building F were, on average, over 28°C for 40% of the time while Building G suites were over the same threshold for 20% of the time, as shown in Figure 12. It is interesting to note that despite the possible afternoon shading provided by Building G and greater daily A/C use, Building F was considerably warmer than the near-identical Building G at the start of the summer. Towards August, the temperature differences between these two buildings decreased. It is unclear what is driving this trend or the higher temperature differences at the start of the summer.

To explore the effects of orientation on indoor temperatures, North- and South-facing suites in Buildings A and B were compared to one another as shown in Figure 13. If more than one suite is available at a particular location, a suite that was representative of the average was chosen for the plot. Two days are shown: a typical summer day, when the average exterior temperature was 21°C, and a hot summer day when the average exterior temperature was 28°C. Suites with air conditioners are excluded from these comparisons. In addition, the monitored suites were all on the second floor (with the exception of Building B, South, which was on the third floor), minimizing any potential differences in temperature due to building height. Based on the t-test and f-tests, the mean and variance from each sample of data were found to be significantly different.

The hot day comparisons, shown in Figure 13, indicate that the South-facing suites in both buildings are considerably warmer than the North-facing suites. Temperatures on the South side also increase several degrees midmorning; these high temperatures are then maintained for the remainder of the day. It is also interesting to note that high indoor temperatures between 28°C and 31°C are maintained during nighttime at both elevations, while the exterior temperature drops to 22°C. Given that the previous day (July 28) had an average temperature of 28°C, these data indicate that suites do not experience a cooling benefit from the diurnal temperature swing.

The average summer day in June also exhibited a large difference between the indoor and outdoor temperatures. However, temperature differences between the orientations were a lot closer for both buildings. In fact, average conditions in Building B show a slightly higher temperature at the north than at the south. large deciduous trees are located along the South end of the site, which can help shade units located at that elevation. The data here could be influenced by differences relating to resident behavior in the individual units.

The effects of East and West orientation on temperature were also explored. Throughout the day, the temperature increases above 30°C were observed at 7 a.m. on the East side and 5 p.m. on the West side. However, the East-facing suite was consistently hotter than the West-facing suite, which could have been partially shaded by Building D, which is situated in close proximity.

Next, the influence of building height on indoor temperature was explored as shown in Figure 14 for a hot summer day. Building E was used instead of the taller Buildings F and G because a larger number of suites without air conditioning were available for the comparisons. The two units included in this analysis face East to eliminate the effects of orientation on temperature differences.

The typical summer day is not shown because the difference between suites on the third and ninth floors is, on average, within the sensor uncertainty. The t-test and f-tests for this comparison also indicated that the mean and variance from each sample of data were not significantly different because the suite temperatures were so similar. On the other hand, there was nearly a 2°C difference between the top and bottom floors

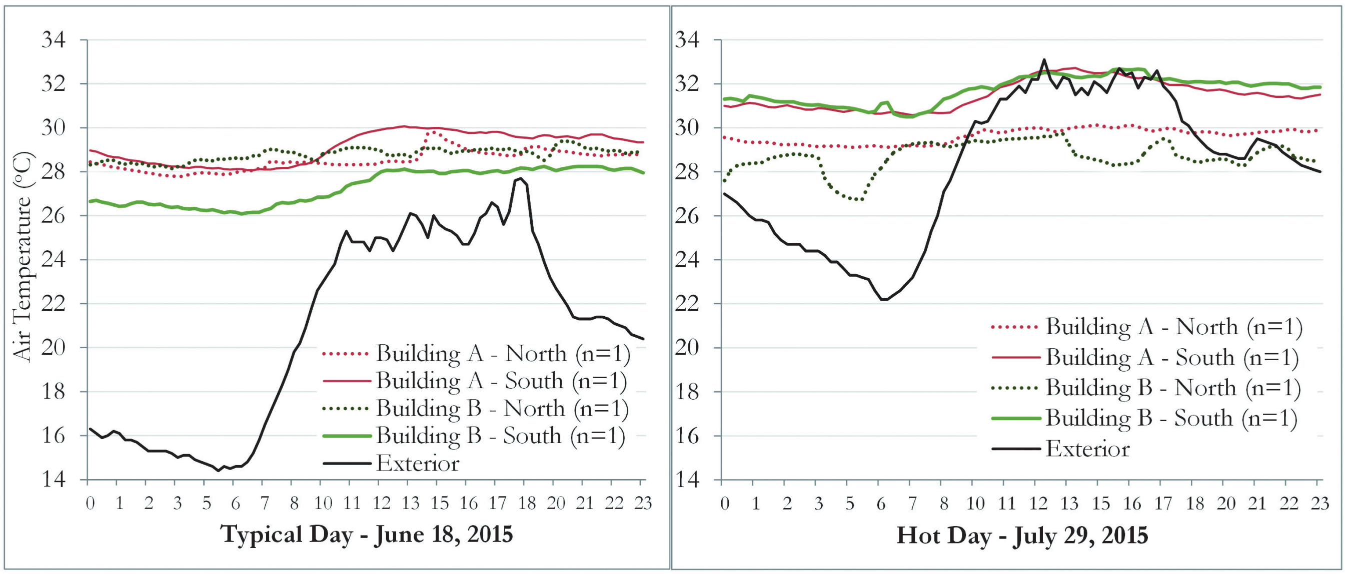


Figure 13 Influence of suite orientation on air temperature in Buildings A and B.

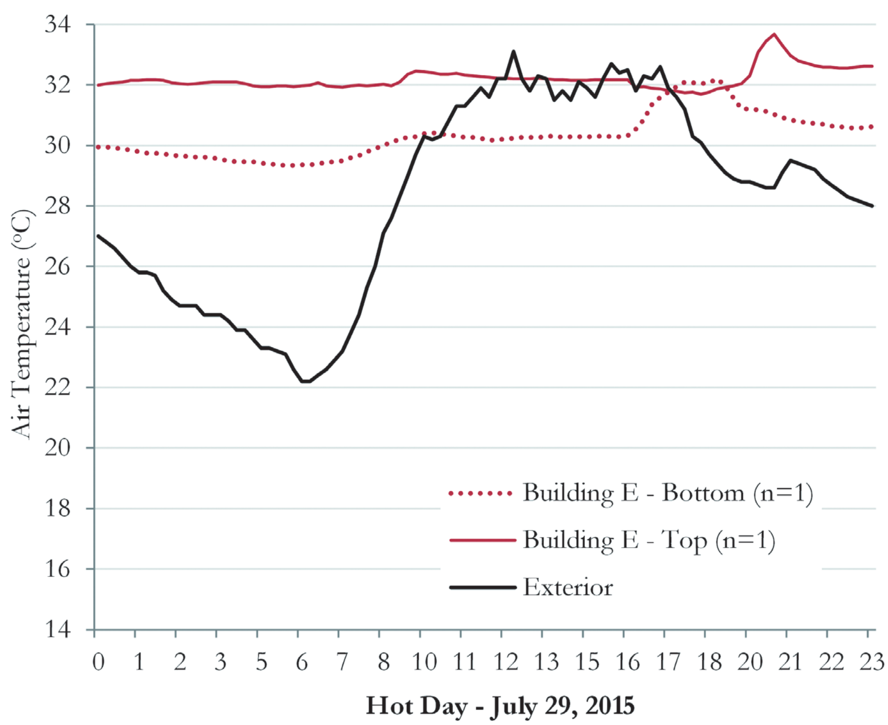


Figure 14 Influence of suite height on air temperature in Building E.

for the hot summer day. As shown in the other buildings, diurnal changes in the outdoor temperature do not translate to similar changes indoors.

COMPARISON AND AGREEMENT

The purpose of the comparison between the survey responses and monitoring data was to determine if the surveys present a consistent indication of thermal comfort issues during the summer months, thereby eliminating the need for costly long-term in-suite monitoring.

First, the survey responses related to thermal comfort satisfaction were compared with the suite air temperature on a site basis in Figure 15. Each data point used to construct the box plot is the average temperature in each suite over the entire summer period inclusive of June, July, and August. Only suites with at least 99% of the possible data collected this three month period were included here.

For Sites 1 and 3, the "Too warm" responses are associated with higher interior temperatures when compared to the "Just right" responses. However, the median temperatures associated with the "Too warm" responses are not consistent between sites. This is problematic if these data are used to identify a threshold at which most residents would be comfortable as there is no agreement between sites on which temperatures are "Just right" and which are "Too warm." Similarly, an Israeli study also found poor correlations between operative temperature and perceived thermal comfort (Becker and Paciuk 2009).

As air temperature alone does not yield a consistent correlation to survey responses about perceived thermal comfort, the air temperature, MRT, and relative humidity data were used to determine the percentage of time the suite was outside of the comfort zone. To determine this percentage, the conditions in the suite for each 15-minute increment were compared to a zone where an estimated 80% of the population is likely to be comfortable. This comfort zone was generated by the adaptive method in the Centre for the Built Environment's Thermal Comfort Tool based on ASHRAE Standard 55-2013 using the observed air temperature, MRT, and relative humidity data (Hoyt et al. 2013). It was assumed that resident's clothing level and metabolic rate were 0.5 clo and 1.0 met, respectively. These values are indicative of an average person in a seated and relaxed position. It was also assumed the air speed in the suite was 0.15 m/s. No data were collected on these three parameters but a sensitivity analysis was conducted on the air speed. Decreasing the airspeed to 0.1 m/s resulted in increasing the percent of time outside the comfort zone by an average of 2%, because reducing air circulation will have increased discomfort in units where overheating is an issue. Increasing the airspeed to 0.2 m/s resulted in decreasing the percent of time outside the comfort zone by an average of 6%.

A significant limitation of this approach is the inability to verify the assumptions made in order to generate the comfort zone. For example, by assuming a single air speed in all suites, the time spent outside the comfort zone could be overestimated if air speeds generated by a fan or breeze through an open window are greater than 0.15 m/s. Similarly, they could be underestimated in stagnant air conditions, as illustrated by the sensitivity analysis. Nevertheless, the

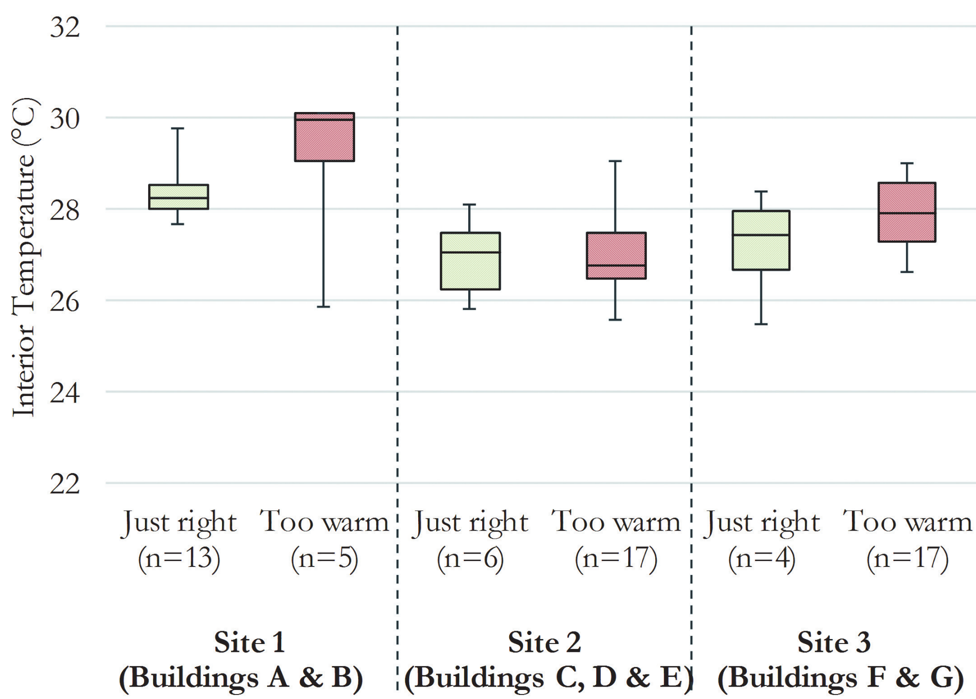


Figure 15 *Influence of interior air temperature on thermal comfort survey responses.*

comfort evaluations provide a way to evaluate the indoor conditions and allow for comparisons between the buildings based on a standard set of assumptions. Figure 16 shows how the percentage of time outside the assumed comfort zone relates to the respective survey responses from each suite. All suites were outside the comfort zone due to the high temperatures.

Similar to the air temperature analysis, there was no consistent percentage of time outside the comfort zone associated with the "Too warm" responses. Furthermore, there was a greater variation in the range of percentages that corresponded to a particular survey response when compared to the air temperature ranges in Figure 14. This increased variability was likely due to the uniform assumptions made about the comfort zone for all suites. In reality, there would be variations in air movement, clothing level, and metabolic rate impacting the actual thermal comfort perceptions of the residents.

Despite the lack of consistent conditions associated with each survey response, the differences between survey responses within each site and between the sites themselves were investigated further. A number of factors related to the occupants and the building could contribute to these differences. Although the conditions in Buildings A and B were the warmest and were outside the comfort zone for the greatest amount of time, residents were also the most satisfied with the thermal comfort in their suites. This paradoxical finding could also be because of incorrect assumptions in the comfort zone model or because the senior residents have fundamentally different behaviors or preferences compared to the residents in other buildings, as discussed earlier (e.g., Kenny et al. 2010). Given the prevalence of daily fan use identified in the survey responses for these two buildings, as shown in Figure 9, it is possible that the air speed in the comfort zone model is underestimated. A higher air speed can potentially reduce the time spent outside the comfort zone.

The influence of A/Cs was also investigated as shown in Figure 17. While A/Cs clearly reduce the median temperature in the suite compared to suites without A/C, the time these suites are above 28°C is still 65% and 55% for Buildings A and B, respectively. Therefore, either A/C units are inadequate for cooling these spaces or the residents are using them infrequently.

The different metabolic rates associated with age and activity level of residents may also be a contributing factor. Buildings A and B house seniors who may be less mobile than residents in the other buildings, contributing to a lower metabolic rate and perhaps a tolerance of higher temperatures despite a greater vulnerability. Through anecdotal evidence, some of the residents of Buildings A and B have difficulty opening and closing their windows which, if left closed, could contribute to higher interior temperatures. The New York City study found that some seniors thought it was incorrect to use fans with the window open and so kept windows closed during fan use (Lane et al. 2014). Another factor contributing to the comfort of the residents in Buildings A and B is the presence of a cooling center in the common area where many residents spend their time. Despite high in-suite temperatures, perhaps the residents perceive greater comfort in their buildings compared to the other sites because of access to a cooled space.

Sites 2 and 3 had greater numbers of residents reporting conditions were "Too warm." To explore the differences in conditions associated with the thermal comfort survey responses for the remainder of the sites, the responses were plotted by building as shown in Figure 18.

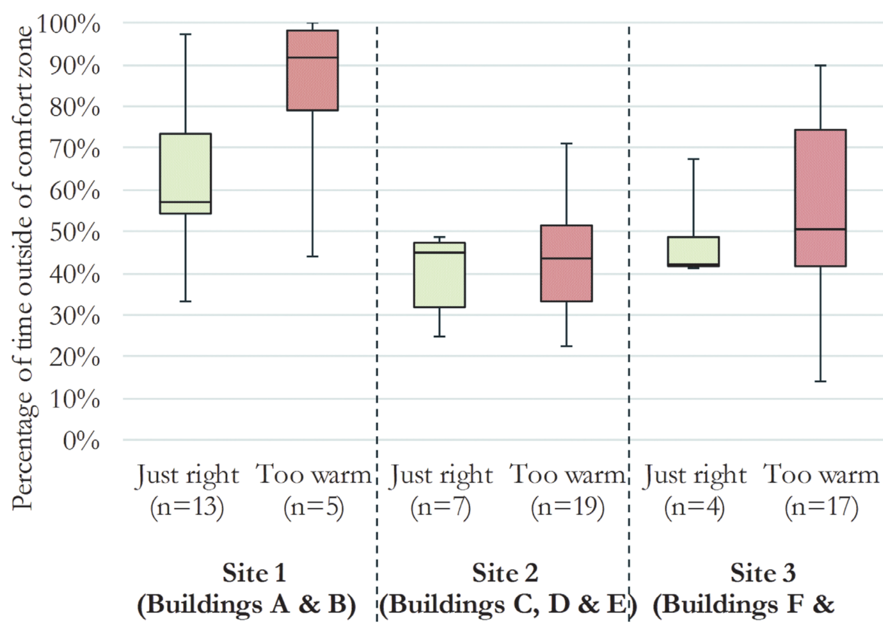


Figure 16 *Influence of time outside the comfort zone on thermal comfort survey responses, by site.*

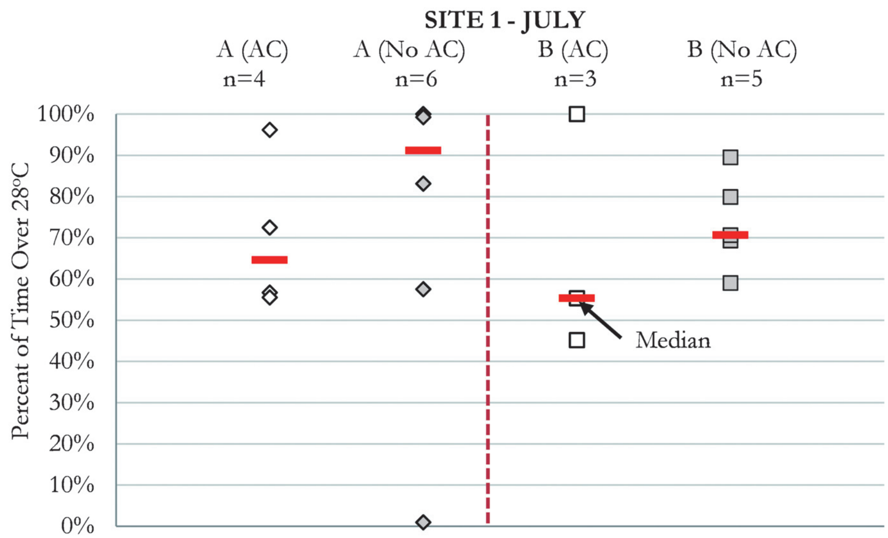


Figure 17 *Influence of interior air temperature on thermal comfort survey responses.*

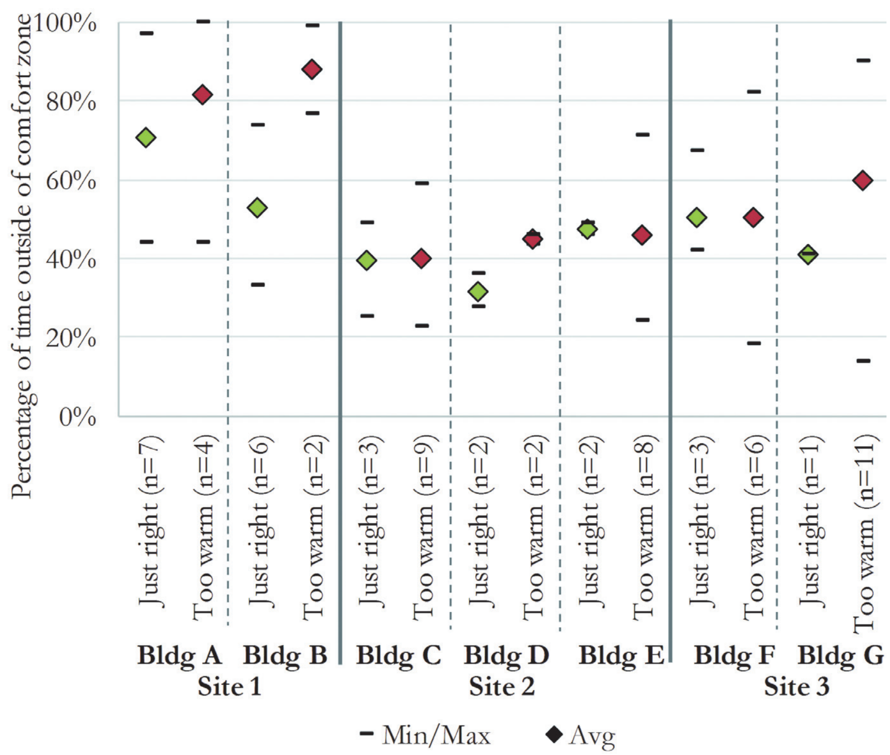


Figure 18 *Influence of time outside the comfort zone on thermal comfort survey responses, by site.*

As observed at the site-level analysis, there is little difference between the average time spent outside the thermal comfort zone and the resident thermal comfort survey response, though the variation of the "Too warm" conditions is generally greater than the "Just right" conditions on Sites 2 and 3. This could indicate that resident perceptions significantly affect what conditions are considered to be "Just right" or "Too warm," with some residents being more accepting of the "Too warm" conditions.

Buildings C–G are taller (7–19 stories) than Buildings A and B (4 stories each); thus, the majority of the monitored suites in Buildings C–G cannot benefit from shading from trees. However, given their height, they may benefit from more natural ventilation due to greater wind speeds at these heights, provided the windows and/or balcony doors are kept open. However, no data were gathered on air speed, so this hypothesis cannot be confirmed.

CONCLUSIONS AND IMPLICATIONS FOR RETROFIT PROCESS

The monitoring and survey data has shown that significant overheating occurs during the summer months across the seven subject buildings. More than half of survey respondents reported conditions were "Too warm" during summer months. Thermal dissatisfaction appears to increase with height of building; however, this trend is not related to stack effect. Instead, it is suspected that exposure to solar radiation as well as resident behaviors and preferences are influencing thermal dissatisfaction. The monitoring data collected showed extremely high interior air temperatures throughout the summer, where all buildings saw interior temperatures exceeding 26°C more than half the time. These high temperatures meant that suites fell outside the thermal comfort zone as evaluated using the ASHRAE Standard 55-2013 adaptive method with a set of uniform assumptions for clothing level, metabolic rate, and air speed.

Differences were observed between the resident survey responses and the monitoring data. For example, Buildings A and B had the highest recorded temperatures and the highest percentage of time spent outside the comfort zone. However, the residents in these buildings were also the most satisfied with the thermal comfort in their suites compared to Buildings C–G. Based on the data presented here, it is not appropriate to use surveys in lieu of in-suite monitoring to reliably identify overheating, as the temperatures and time spent outside of the comfort zone do not correspond to the same thermal comfort response across all buildings and sites. Therefore, it may not be appropriate to use an air temperature threshold to ensure comfort, unless the temperature is sufficiently low, which may be impractical to maintain and could result in conditions that are considered too cool for some residents.

Additional types of in-suite data are required to generate a more accurate thermal comfort zone. In particular, air speed measurements would be a valuable addition to this analysis. This work also suggests that solar exposure is a contributor to thermal discomfort. A more targeted study of how the use of blinds, curtains, or other solar shading can impact thermal comfort is also needed. Light meters located near windows and/or a more representative measure of MRT would provide an indication of exposure to solar gains and whether the residents used shading devices.

Overheating in suites can have several implications for the building retrofits. Survey respondents who considered conditions "Too warm" also reported frequent use of A/Cs and fans which, particularly in Buildings F and G, may not be the most effective way of combating overheating. With extreme temperatures persisting throughout the summer, this frequent use of A/Cs and fans can result in high electricity consumption across the seven buildings. To improve the thermal comfort, passive measures that reduce solar heat gain as well as cooling strategies are strongly recommended. The installation of exterior blinds and/or replacing windows with those that have a low solar heat gain coefficient can help reduce solar heat gain during the summer. These types of measures should be considered in particular for Buildings A–B, where the majority of the windows are not shaded by balcony overhangs. Resident education about the impact of blinds, shades, and curtains on thermal comfort is also essential for these passive measures to be effective. In addition, adding conditioned spaces on site or providing a dedicated outdoor air supply or cooling to each suite with air sealing measures can help to reduce extreme temperatures. However, these active measures should only be contemplated after the passive measures have been adopted.

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