Title

Field evaluation of occupant satisfaction and energy performance in eight LEED-certified buildings using radiant systems

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1. Abstract

In this study, we present the results of a post-occupancy assessment on thermal comfort, indoor air quality, and acoustical quality from 568 occupant surveys in eight LEED-certified buildings with radiant heating and cooling systems, and trends in low-energy consuming buildings based on building characteristics, radiant design, and building operator interviews. This study follows-up on a quantitative assessment of 60 office buildings that found radiant and all-air buildings have equal satisfaction with indoor environmental quality, with a tendency for increased thermal satisfaction in radiant buildings. Our objective was to investigate reasons of comfort and discomfort in the radiant subset, and to relate these to building characteristics and operations strategies. Our analysis revealed that the primary sources of temperature dissatisfaction are lack of control over the thermal environment (both temperature and air movement) and slow system response, both of which were seen to be alleviated with fast-response adaptive opportunities such as operable windows and personal fans. There was no optimal radiant design or operation that maximized thermal comfort, and building operators were pleased with reduced repair and maintenance associated with radiant systems compared to all-air systems. Occupants reported low satisfaction with acoustics. This was primarily due to sound privacy issues in open offices which may be exacerbated by highly reflective surfaces common in radiant spaces. Indoor air quality satisfaction appears to be aligned with thermal comfort more than ventilation strategy, and buildings with low annual energy consumption take advantage of free cooling and avoid heating and cooling in the same day or same season.

Keywords: Occupant satisfaction, Indoor Environmental Quality, Radiant systems, Post-occupancy evaluation, Thermal comfort

2. Introduction

In the United States, commercial buildings consumed 18% of primary energy in 2018, and 31% of that was related to HVAC systems (EIA 2019). The Intergovernmental Panel on Climate Change (IPCC) has publicized the outcomes of climate change (IPCC 2014; Hoegh-Guldberg et al. 2018) and have driven policies to reduce carbon emissions. With the current outlook, buildings and HVAC systems may need to address future weather events that are outside the existing range of design conditions and dynamic time-of-use energy pricing that promote renewable energy sources. High thermal mass radiant buildings have numerous benefits for climate responsible designs. They have the potential to be resilient against uncertain weather conditions and utility pricing because of their flexibility in operating times, they use water instead of air which is a more energy efficient medium for energy transportation, and they can achieve high COPs as a result of high temperature cooling and low temperature heating. Researchers have looked at the range of appropriate applications and developed design guidelines and research areas for radiant heating and cooling systems (Babiak, Olesen, and Petras 2009; Moore, Bauman, and Huizenga 2006; Bauman et al. 2019).

In addition to the energy benefits, industry and designers have often referenced potential thermal comfort implications from radiant systems. According to results from the Center for the Built Environment (CBE) web-based occupant survey, temperature, acoustics, and perceived indoor air quality (IAQ) are the IEQ parameters that typically receive the lowest occupant satisfaction ratings in office buildings (Frontczak et al. 2012). As we learn more about occupant comfort and health implications from the built environment, building practitioners look to avoid causing adverse effects on occupants.

2.1. Energy Performance

Radiant systems have proven to be a successful strategy for low-energy buildings. A recent report on Zero Net Energy buildings found that the majority (64%) of 23 featured buildings use radiant heating and/or cooling (Higgins, Miller, and Lyles 2015). A similar study found that radiant buildings generally had energy use intensity (EUI) 14 to 58% lower than comparable buildings from the DOE Building Performance Database, and ENERGY STAR Scores above 75 (the certification requirement) (Higgins and Carbonnier 2017). In the latter study, it was noted that the majority of the buildings were designed to be low-energy, many seeking LEED platinum, so building features beyond the heating and cooling system likely contribute to the low EUIs.

High thermal mass radiant systems use water as the heat transfer medium, which has a much higher thermal capacity than air, making it more effective. Simulation, laboratory, and field studies have shown the potential energy benefits of radiant systems compared to all-air systems (Stetiu 1999; Niu, Zhang, and Zuo 2002; Tian and Love 2009). The primary energy benefits include:

- Higher chilled and hot water equipment efficiencies due to relatively high temperature water for cooling and low temperature water for heating, which also means they can use low-energy sources such as groundsource heat pumps and cooling towers, resulting in lower primary energy consumption (Oxizidis and Papadopoulos 2013; Raftery et al. 2017).
- Peak load shifting and shaving (Feng, Schiavon, and Bauman 2013; Lehmann, Dorer, and Koschenz 2007), which can be important under future energy rate structures, as well as improving chilled water plant efficiency.

- Reduced electricity consumption by using pumps versus fans to transport energy, especially when operated with pulsed flow (Lehmann et al. 2011).

However, energy benefits may not always be realized. Studies have shown that building design, operating practices, and climate can reduce or eliminate any potential savings for a radiant system. For example, areas with high latent loads or with high potential for free cooling through economizers or passive cooling may observe less benefit (Stetiu 1999; Tian and Love 2009; Feng and Cheng 2018); although research has shown potential low-energy solutions for hot and humid climates (Niu, Zhang, and Zuo 2002). Similarly, very few existing radiant buildings capture benefits from higher and cooler water temperatures because the water supply typically serves both the radiant system and ventilation or supplemental air systems (Paliaga et al. 2017).

2.2. Thermal comfort

According to the PMV-PPD model there are six factors that contribute to thermal comfort in the built environment (ANSI/ASHRAE 2017). Heating and cooling systems, in combination with building envelopes, should be designed to maintain acceptable comfort conditions for an expected range of occupant clothing and metabolic rates by controlling the four environmental conditions: air temperature, mean radiant temperature, air speeds, and humidity. Radiant heat loss accounts for 58 to 60% of the sensible heat loss from the human body under typical office working conditions (ASHRAE 2017); meaning that mean radiant temperature is equally as important as air temperature to thermal comfort. Additionally, the systems should avoid causing local thermal discomfort that can result from radiant asymmetry, vertical air temperature differences, unwanted air movement, and ankle draft risk (ANSI/ASHRAE 2017; Liu et al. 2017).

The commonly cited reasons for improved thermal comfort in radiant buildings are that they:

- Result in uniform temperature (Babiak, Olesen, and Petras 2009; ASHRAE 2017) and minimized vertical air temperature gradient (Imanari, Omori, and Bogaki 1999; Jia, Pang, and Haves 2018; Le Dréau and Heiselberg 2014; Catalina, Virgone, and Kuznik 2009).
- Reduce unwanted air movement in heating (commonly referred to as draft) by separating heating and cooling from ventilation. Ventilation-only air systems supply lower volumes of air at lower velocities than traditional all-air systems (Imanari, Omori, and Bogaki 1999; Catalina, Virgone, and Kuznik 2009; Novoselac and Srebric 2002; Loveday et al. 1998).
- Reduce or eliminate discomfort from hot or cold surfaces (i.e., radiant asymmetry). Studies have shown that if surface temperatures for radiant systems are within specified limits, they do not cause discomfort (Loveday et al. 1998; Fanger et al. 1985), and radiantly heated floors can reduce discomfort from cold floors (ASHRAE 2017). Radiant systems may actually reduce radiant asymmetry because, inherent to radiant heat exchange, active radiant surfaces exchange heat with all other viewable surfaces, and

mean radiant temperature is closer to air temperature in radiant spaces than in all-air spaces (Dawe et al., In press).

Although previous studies have speculated on potential sources of improved thermal comfort in radiant buildings, the literature is not conclusive on whether radiant buildings have significantly higher thermal comfort than all-air buildings. From a literature review comparing thermal comfort for all-air and radiant systems, (Karmann, Schiavon, and Bauman 2017) identified five studies that found no distinct preference, and three studies which found thermal conditions or occupant satisfaction were slightly improved for radiant systems. Of these three studies, only two used occupant surveys to assess thermal comfort, one of which was only for a conference room within an all-air building, and the third was a controlled laboratory experiment using physical measurements to assess thermal comfort. All studies had relatively small sample sizes (e.g., only occupants from a single building each, small-scale laboratory experiments, or building simulations).

In a comprehensive study, (Karmann et al. 2017) compared satisfaction from occupant surveys in 26 radiant and 34 comparable all-air buildings (1,645 and 2,247 surveys, respectively) and found equal satisfaction with indoor environmental quality between the two building groups, with a tendency towards improved temperature satisfaction in radiant buildings, but not a practically significant difference. This extensive comparison study, using the largest database of its kind to date, reduces the influence from non-HVAC related factors between buildings. The results show that radiant systems will have equal, or no worse, thermal comfort than all-air systems.

2.3. Indoor air quality

Separating the cooling load from the ventilation makes dedicated outdoor air system (DOAS) more cost feasible, and therefore, more common in radiant buildings than all-air buildings. DOAS may improve IAQ by eliminating air recirculation, and can be especially effective when provided through displacement ventilation. However, a radiantly cooled ceiling can counteract stratification created by displacement ventilation and designers should consider the system interactions to benefit from both (Novoselac and Srebric 2002; Loveday et al. 1998; Hao et al. 2007; Behne 1999; Schiavon et al. 2012).

Although indoor pollutant levels may be lower with DOAS and displacement ventilation, study results have found that occupant perception of IAQ is more dependent on thermal comfort including temperature, air movement, and humidity, than pollutant levels, (Melikov and Kaczmarczyk 2012; Zhang, Arens, and Pasut 2011; Humphreys, Nicol, and McCartney 2002; Fang et al. 2004). Subjects associated poor IAQ with thermal discomfort, both too warm or too cool temperatures, and that IAQ was better when air movement was present in warmer and/or humid conditions, especially when it was towards the breathing zone.

2.4. Acoustics

Acoustics typically receives the lowest satisfaction rating in office buildings (Frontczak et al. 2012), and assessments encompass both noise in the workspace and sound privacy (i.e., the ability to hold a private conversation). Radiant buildings present both benefits and challenges for acoustical quality. The low airflow rates for ventilation-only allow for smaller fans and results in less air traveling through ducts, reducing irritating noise, but also reducing white noise or noise masking abilities (Oxizidis and Papadopoulos 2013; Hao et al. 2007). Radiant spaces typically have exposed concrete or metal surfaces, which can increase noise transfer. A main acoustical concern for office buildings has been sound privacy and noise levels in open-office layouts. Strategies such as acoustical panels and carpets that are usually employed to help reduce sound travel are less often included in radiant designs because they reduce the system's capacity (ASHRAE 2017), but the reduction is only 11% when 47% of the ceiling is covered with free-hanging panels, and the reduction can be more than compensated in this scenario by the use of ceiling fans to increase convective cooling (Karmann et al. 2018). Despite these concerns for radiant systems, Karmann et al. (2017) found that radiant and all-air spaces do not have statistically different acoustical satisfaction.

2.5. Objectives

We selected eight thermally massive radiant buildings from the (Karmann et al. 2017) dataset to assess occupant satisfaction surveys and radiant system design and operation. Thermally massive buildings include thermally-activated building systems (TABS), where radiant piping is embedded into the structural concrete, and embedded surface systems (ESS), where radiant piping is embedded into a topping slab with or without insulation. This study builds on the previous work by thoroughly investigating trends and contributing sources for energy performance and occupant satisfaction with temperature, acoustics, and perceived IAQ directly from occupant surveys. Karmann, Schiavon, and Bauman's (2017) previous thorough review of thermal comfort studies found that only two out of eight conclusive studies used occupant surveys taken in their workplace, and two used human subject responses from laboratory experiments. The remaining four studies used PMV-PPD to evaluate thermal comfort from physical measurements or simulated results. Thermal comfort is a state of mind and can be influenced by several factors; furthermore, research has suggested that the PMV-PPD model has low prediction accuracy (Cheung et al. 2019), which makes using subjective occupant responses more relevant.

The goal of this study is to identify trends in energy performance and occupant satisfaction across eight buildings using building characteristics, HVAC system design information, and occupant perception of their indoor environment. Each study building is designed and operated differently, as well as potentially having different occupant populations; therefore, there are numerous uncontrolled variables between buildings. We identify what appear to be trends across buildings, as well as interesting features that may be unique to a single building.

3. Methods

3.1 Data Collection

The study presented here was part of a larger CBE Radiant project which investigated several aspects of radiant heating and cooling systems, including control sequences, design and operation, and occupant comfort. Through this, the CBE Radiant project team collected design information on over 20 radiant buildings and conducted occupant satisfaction surveys using the online CBE Occupant Satisfaction Survey (Higgins and Carbonnier 2017; Karmann et al. 2017; Zagreus et al. 2004). This data was collected in the fall of 2016.

For this analysis, we assessed IEQ satisfaction using the previously collected occupant surveys. We are assessing temperature, acoustics, and IAQ with occupants' satisfaction, not with measured values. We selected eight buildings with different levels of occupant temperature satisfaction and annual EUI. We deliberately chose a mix of building performance so we can better understand successful strategies and areas that need to be further addressed. In addition to this data, we conducted interviews with building operators in six of these buildings.

3.1.1. Building and system characteristics

The CBE Radiant project team developed four online forms to collect information on (1) radiant design and operation, (2) building characteristics, (3) energy performance, and (4) facility and operations. The surveys were distributed to the appropriate contacts, such as the design engineer or building operator. The respondents completed the forms to the best of their knowledge of the system or building at that time. Results of the whole building energy performance analysis are provided by (Higgins and Carbonnier 2017)

A limitation of the forms is that they reflect the operation at that time and do not have the ability to capture system-specific details. For example, in the radiant design and operation survey, "How do you control the zone loops?" had four response options: "constant flow and constant temperature", "constant flow and variable temperature", "variable flow and constant temperature", "variable flow and variable temperature". For a response that includes variable temperature, we did not capture how the temperature varies and in response to what, such as outside temperature or the previous day's indoor temperature. Therefore, buildings with different underlying strategies are categorized similarly based on form responses. Without review of individual control sequences, we cannot always identify those differences.

3.1.2. Occupant surveys

The CBE IEQ Occupant Satisfaction survey asks respondents to rate their satisfaction with IEQ parameters using a seven-point scale from very dissatisfied to very satisfied, with a neutral response allowed (Zagreus et al. 2004). When respondents were dissatisfied with a feature (i.e., slightly dissatisfied, dissatisfied, or very dissatisfied), they were asked additional branching questions about the sources of their dissatisfaction using pre-defined options and an open-ended response. On the other hand, when respondents were neutral or satisfied, they were not asked additional questions about the source of their comfort. This is done as a way of reducing the length and potential survey fatigue, although we recognize it limits our ability to dive more deeply into the reasons behind positive responses.

Similar to the building and radiant design forms, the surveys have limitations due to the pre-defined options, which may not capture nuances or could be interpreted differently by occupants. The survey is voluntary, and respondents are not required to answer every question, so survey completeness and response rate is always a concern. Additionally, the occupant survey used in this analysis is meant to capture occupants' subjective perceptions of their typical experience in the space, not of specific episodic events (e.g., right-now survey).

3.1.3. Interviews

For the building operator interviews, we attempted to reach the primary engineer or another contact knowledgeable of the radiant system and building operation. We conducted one-hour interviews for six buildings. The goals of the interviews were to:

- Understand the balance and synergies between energy performance and occupant thermal comfort;
- Gain further insight into occupant feedback for IEQ parameters;
- Identify lessons learned during commissioning and operation; and,
- Discuss the advantages and disadvantages of radiant systems for energy consumption, occupant comfort, and operation.

3.2. Data analysis

Karmann et al. quantified occupant temperature satisfaction in 26 radiant buildings, the details of which can be found in (Karmann et al. 2017). For this study, we base findings on an in-depth qualitative analysis of building design, occupant feedback, and building operator interviews. Occupants provide satisfaction ratings on a seven-point scale; however, thermal comfort is subjective because it is a psychological state of mind. We used occupant open-ended responses and insight gained from building operator interviews to interpret and contextualize occupant responses. As much as possible, we identified trends that appear across multiple buildings.

Our analysis includes whole building annual energy performance and occupant satisfaction for three IEQ parameters: temperature, perceived IAQ, and acoustics. There is no guidance or method to define a satisfactory building across multiple IEQ parameters, and attempts to develop a method to calculate whole building satisfaction from individual IEQ parameters have yielded different results in weighting the IEQ parameters (Heinzerling et al. 2013). Additionally, there are no standard methods for how to assess the distribution of occupant responses amongst the satisfactory bins; even in ASHRAE Standard 55, satisfactory votes are grouped together without regard to differences between "slightly" to "very". Due to the lack of guidance in this area, we did not organize buildings based on performance, but provide an average percent satisfied (including votes from +1 (‘slightly satisfied’) to +3 (‘very satisfied’)) across the three IEQ parameters, weighting each parameter equally.

The surveys directly inform sources of discomfort, but we had to infer sources leading to comfort. While there is an opportunity for all respondents to provide an open-ended response to describe satisfaction with IEQ parameters, neutral and satisfied respondents rarely did so except when asked about overall satisfaction in the building. Therefore, to inform what factors drive occupant satisfaction, we looked at which reasons respondents never or rarely identified as sources of dissatisfaction, identified features that exist in buildings with high satisfaction, incorporated building operator feedback, and reviewed open-ended responses if provided.

We were only able to assess energy consumption using whole building energy data for a single year, which may not be representative of the building on average and does not provide system level detail. Given these constraints, we suggest trends and operation strategies that appear to be related to energy performance based on system design and building operator interviews.

Lastly, Building 5 has two distinct occupancy types with substantially different satisfaction responses: workers in an office area and workers in a dining/café area. Radiant systems in dining/café areas are not common at this time, and to maintain consistency of occupancy type across the eight buildings, we excluded responses from the dining/café area.

4. Results and Discussion

Table 1 presents the annual EUI and occupant satisfaction results for each IEQ parameter, and the average satisfaction results across parameters. The buildings are organized by alphabetical order of building name (not shown). ASHRAE Standard 55 recommends that response rate should exceed 35% for occupancy greater than 45 people for surveys to be representative (ANSI/ASHRAE 2017). The suggested 35% response rate was not achieved in four of the buildings, as seen in italicized text in Table 1. Even when response rate was less than recommended and cannot be used to generalize the building, we can still view responses as suggestive of trends. There are several factors that can impact overall occupant satisfaction and whole building energy performance beyond the heating and cooling system that we could not feasibly control for between buildings. The findings are based on 568 occupant surveys and six building operator interviews.

Table 1. Building groupings based on annual EUI and percent of occupants satisfied IEQ parameters

Bldg ID	Response rate (total occupancy)	EUI[a] (kWh/m^2)	% Satisfied[b] Temperature	IAQ	Acoustics	Average % Satisfied
3	62% (n=125)	38	63%	85%	25%	58%
8	37% (50<n<100)	486	32%	46%	40%	39%
5[c]	*20% (n=200)*	*NA*	*61%*	*74%*	*57%*	*64%*
1	*27% (n=175)*	*75*	*79%*	*85%*	*51%*	*72%*
2	*4% (n=1,000)*	*114*	*75%*	*90%*	*26%*	*63%*
7	48% (n=190)	555	46%	70%	24%	47%
4	53% (n=68)	151	64%	83%	25%	57%
6	*28% (n=750)*	*NA*	*60%*	*60%*	*37%*	*52%*

[a] Energy Use Intensity, from (Higgins and Carbonnier 2017), converted to kWh/m^2

[b] Considering votes from +1 ('slightly satisfied') to +3 ('very satisfied')

[c] Building B2 IEQ satisfaction was assessed using the office portion only

4.1. Building and system features

Table 2 presents the color-coded performance for each of the four performance parameters, as well as information about climate and building characteristics. Each of these eight buildings achieved LEED certification, many reaching Platinum, indicating that they are were all designed as high-performing.

[b] In case the building was renovated, we indicated original year of construction in parenthesis

[c] Adaptive opportunities may refer to fast-response actions that either affect groups (i.e., operable windows, ceiling fans) or individuals (i.e., desk fans, heaters). We used an asterisk to indicate opportunities supporting individual actions.

Table 3 further provides system operation information. The radiant system operation reflects controls at the time the surveys were completed in fall 2016 for proper comparison between system operation and occupant responses. More details on building characteristics and system operation can be found in the **Error! Reference source not found.**.

Table 2. Building characteristics and performance

Bldg ID	Performance[a]	Function	Area (ft^2)	ASHRAE Climate	Year built (original)[b]	Radiant type	Certifications	Adaptive opportunities[c]
3	E T IAQ A	Office	52,000	4C: Mixed-marine	2015 (1910)	ESS floor	LEED Platinum, Living Building Challenge	Operable windows, ceiling fans
8	E T IAQ A	Library	<50,000	4C: Mixed-marine	2012	TABS ceiling	LEED Gold	Operable windows, desk fans*
5	E T IAQ A	Office + multi-purpose	200,000	3B: Warm-dry	2010	ESS floor	LEED Platinum	Operable windows, desk fans*, ceiling fans
1	E T IAQ A	Office	172,400	3C: Warm-marine	2003	TABS floor	LEED Platinum, Net zero	Operable windows, desk fans*, heaters*, thermostat
2	E T IAQ A	Office	360,000	5B: Cool-dry	≤ 2010 (renovated)	TABS ceiling	LEED Platinum	Operable windows, desk fans*, ceiling fans
7	E T IAQ A	Office	44,000	3A: Warm-humid	2012	ESS ceiling	LEED Platinum	Desk fans*, heaters*
4	E T IAQ A	Office	16,150	4C: Mixed-marine	2015	TABS floor	LEED Platinum	Trickle vent, thermostat
6	E T IAQ A	Office	203,000	3B: Warm-dry	2010 (1986)	TABS ceiling	LEED Platinum, LEED EBOM	Desk fans*, heaters*, ceiling fans

[a] Performance codes and satisfaction scale:

	Good					Bad
Satisfaction	≥ 90%	75 to <90%	60 to <75%	50 to <60%	40 to <50%	< 40%
EUI (kWh/m^2)	≤ 100	> 100 to 200	> 200 to 300	> 300 to 400	> 400 to 500	> 500

E: Energy Performance
T: Temperature satisfaction
IAQ: Perceived IAQ satisfaction
A: Acoustical satisfaction

[b] In case the building was renovated, we indicated original year of construction in parenthesis
[c] Adaptive opportunities may refer to fast-response actions that either affect groups (i.e., operable windows, ceiling fans) or individuals (i.e., desk fans, heaters). We used an asterisk to indicate opportunities supporting individual actions.

Table 3. Radiant system and ventilation design. Some fields indicate "unknown" where responses were left blank and we were not able to identify the appropriate feature.

Bldg ID	Performance[a]	Radiant type	Operation outside occupied hours	Air temp setpoints[b]	Temperature control[c]	Ventilation type[d]	Ventilation (DOAS)[e]
3	E T IAQ A	ESS (floor)	24/7, setback temperature	68/78 °F	Zone air	MM (change-over)	Overhead
8	E T IAQ A	TABS (ceiling)	24/7	73/79 °F	unknown	MM (change-over)	Underfloor
5	E T IAQ A	ESS (floor)	Turns on before occupancy	70/76 °F	unknown	MM (unknown)	Overhead
1	E T IAQ A	TABS (floor)	Turns on before occupancy	68/74 °F	Average air and slab	MM (concurrent, change-over)	Overhead
2	E T IAQ A	TABS (ceiling)	Turns on before occupancy	71/78 °F	Custom weighted average air and slab	MM (unknown)	Underfloor
7	E T IAQ A	ESS (ceiling)	unknown	70/74 °F	unknown	MV (fully)	Underfloor
4	E T IAQ A	TABS (floor)	24/7	70/75 °F	Zone air and outside air	NV (fully)	Trickle vents
6	E T IAQ A	TABS (ceiling)	24/7, setback temperature	70/76 °F	Zone air	MV (fully)	Overhead

[a] Uses same performance codes and satisfaction scale as Table 2
[b] Zone air temperature setpoints for heating / cooling at the time of the survey
[c] Indicates to which temperature setpoint(s) the radiant system responds
[d] MV: Mechanical ventilation (no operable windows), NV: Natural ventilation, MM: mixed-mode (type: change-over, concurrent, zoned)
[d] All buildings used DOAS; underfloor includes UFAD or displacement ventilation

4.2. Energy performance

We assessed total building energy performance based on a single year of energy consumption, collected by (Higgins and Carbonnier 2017), and identified energy saving trends from the building operator interviews and radiant operation surveys. We were not able to directly assess the energy consumption of the radiant system by itself. In addition, two buildings are campus-style and could not provide building-level energy data, and we were not successful in interviewing operators from the two highest energy consuming buildings. Many of the thermal comfort strategies are in place to also promote low-energy consumption, such as operable windows for free cooling. The following features appear to be related to energy performance in these buildings:

Of the four best energy performing buildings:

- All take advantage of free cooling through operable windows, or trickle vents in one building, with the additional benefit of improved thermal comfort from increased air movement in warm temperatures. At least one of these buildings turns off the radiant system operation to zones where windows are open, and one of these buildings relies solely natural ventilation.

- All have zone air temperature deadband (i.e., degrees between heating and cooling air temperature setpoints) between 4 and 10 °F.
- Three use seasonal changeovers for heating and cooling, so they do not allow the system to heat and cool in the same day. These buildings rely on operable windows, trickle vents, and/or personal control system (i.e., desk fan, heaters) to help maintain comfort during shoulder seasons.
- Only one of the buildings sets chiller temperature higher than traditional values, but none specify that they provide cooling without compressors (e.g., evaporative cooling tower).
- Multiple buildings have high performance envelopes, including sun shading to avoid direct solar heat gains, and reduce heat transfer.

Of the two buildings with poor energy performance:

- Neither have operable windows for free cooling.
- At least one has a supplemental air-cooling system for hot and humid summer conditions that, based on occupant comments, appears to be overcooling the space. This building has the smallest dead band between heating and cooling (4 °F) and also has poor occupant comfort. This small dead band could be causing heating and cooling in the same day, and it could also be the cause of over-cooling in warm weather.

4.3. Thermal Comfort

ASHRAE Standard 55 defines an acceptable thermal environment as one in which at least 80% of the occupants are satisfied (ANSI/ASHRAE 2017). When using a satisfaction survey such as ours with a seven-point Likert scale, ASHRAE Standard 55 has modified the definition of satisfaction over time, as shown in Table 4.

Table 4: Temperature satisfaction by building

Bldg. ID	# of occupant responses (response rate)	Percentage reported for temperature satisfaction		
		% satisfied considering votes from (-1) to (+3)(a)	% satisfied considering votes from (0) to (+3)(b)	% satisfied considering votes from (+1) to (+3)(c)
B1(d)	*23 (27%)*	***96%*** *(e)*	***89%***	*79%*
B2(d)	*47 (4%)*	***93%***	***85%***	*73%*
B3	78 (62%)	**89%**	67%	63%
B4	36 (53%)	**94%**	75%	64%
B5(d)	*17 (20%)*	*78%*	*61%*	*61%*
B6(d)	*207 (28%)*	***88%***	*72%*	*60%*
B7	91 (48%)	76%	53%	46%
B8	28 (37%)	64%	39%	32%

(a) 'Slightly dissatisfied' (-1) is the lowest threshold for a positive vote for thermal acceptability in the ASHRAE 55-2017

(b) 'Neither satisfied not dissatisfied' (0) is the lowest threshold for a positive vote for thermal acceptability in the ASHRAE 55-2013
(c) The thermal comfort definition specifies a clear satisfaction statement
(d) The buildings indicated in italic had a response rate lower than 35%
(e) Bolden text for buildings that meets the ASHRAE 55 target of 80% satisfaction rate

If we consider all the buildings (independently from the response rate), three do not comply with any definition, five buildings comply with ASHRAE 55-2017, two of which also comply with ASHRAE 55-2013, but no buildings were able to meet the thermal comfort definition; although, one building came close at 79%. For reference, the average existing building in the CBE database has 40% of occupants satisfied (considering votes of +1 to +3) with temperature (Karmann, Schiavon, and Arens 2018). We explored occupant feedback further to understand what is driving comments such as:

> *"Insanely comfortable"*
>
> *"This is the most comfortable building I have ever worked in…not too hot or too cold."*

Using the 19 sources of discomfort listed in the occupant survey and occupants' open-ended responses, we identified common factors that influence temperature satisfaction. Occupants that are dissatisfied with temperature are asked to select all of the source(s) that best describe their discomfort (noting again that satisfied occupants do not receive a comparable branching question). We combined responses for two listed options: "thermostat is inaccessible" and "thermostat is controlled by other people" because only one building allowed occupants to make direct changes to the thermostat setpoints, so all remaining responses were interpreted as inability to access and change the thermostat. An occupant's vote was only counted once if both options were selected.

Given that this is a "check all that apply" question and there are a different number of occupants per building, we represent the results slightly differently. Figure 1(a) is expressed as the percentage of dissatisfied votes *across all eight buildings* (n=173), and Figure 1(b) shows the percentage of dissatisfied votes *per building*, while also showing the sample size of number of dissatisfied occupants. It is important to consider both so that conclusions about comfort are not informed only by buildings with large occupancy and large portions of dissatisfied occupants. In a few cases, one or two buildings have the majority of votes for a particular source of discomfort, such as draft from windows, and we consider these as unique to specific buildings rather than general trends.

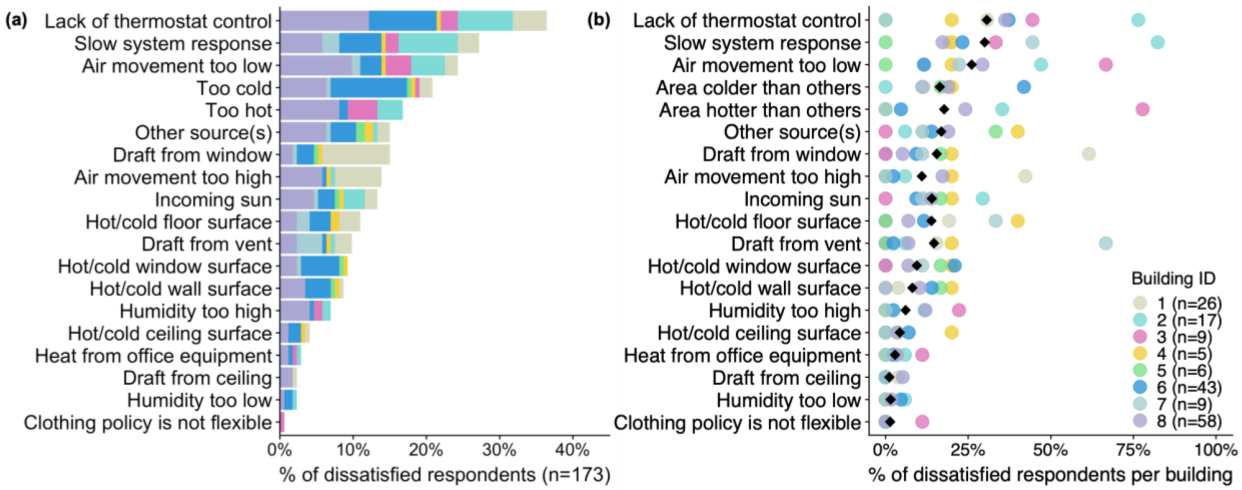


Figure 1. Percentage of dissatisfied occupants (a) across all buildings (n=173) and (b) per building (n by building) for each of the listed sources of discomfort. 173 of 568 occupants expressed dissatisfaction with temperature across all eight buildings.

As seen in Figure 1, there is variability in the top source of discomfort between buildings. This is not surprising because each building has a slightly different design and heating or cooling strategy. Regardless of the variability in votes between buildings, there are clear trends in sources that are always or rarely selected, as represented by the black diamond which is the average percent dissatisfied across each of the individual buildings. Occupants selected "Other source" in all buildings except one. We reviewed their responses and appropriately incorporated them into our assessment.

Based on Figure 1, occupant open-ended responses, and building operator interviews, the following aspects appear to be related to thermal comfort in these buildings. Some of these sources are a direct result of the radiant system, while others are due to the overall strategy of the building, which could be influenced by the radiant system.

Ability to quickly and individually change the thermal environment

The top two causes of discomfort are a lack of thermostat control and slow system response. We know there is no single temperature that will please everyone, and while changing setpoints can improve long-term comfort in radiant buildings, it is not an effective means to instantly address comfort issues, especially in high thermal mass buildings (Ning, Schiavon, and Bauman 2017). As evidence of this, in the two buildings that allow occupants to change temperature setpoints (within limits), occupants indicated that they rarely do this because there is no perceived change in comfort:

> *"I never adjust the thermostat anymore because I have no idea whether it does any good."*

Occupants may not need to fully understand the system operation, but it is important that they have knowledge of what actions they can take to provide both immediate and long-term comfort. As mentioned by a building operator:

> "*Lack of control or understanding may affect [occupant] satisfaction.*"

Adaptive fast-response opportunities, which can affect a group of occupants (i.e., ceiling fans and operable windows) or individual personal comfort systems (PCS) (i.e., desk fans and personal heaters), provide thermal comfort and energy benefits. As suggested by Bauman et al. (Bauman et al. 2015), there is opportunity to integrate PCS with radiant buildings for thermal comfort. One study speculates that fast-response actions decrease work interruptions (Leaman and Bordass 2007). Occupants in six buildings reported using desk fans, four buildings reported personal heaters, four buildings have ceiling fans, and four buildings have operable windows for all or a portion of the radiant spaces. Operable windows are not appropriate in all climates or all seasons due to potential high latent loads. Occupants who reported having adaptive opportunities were pleased:

> *"I don't have much control over temperature. I usually run warm, so I like to have a fan."*

> "*I love the operable windows.*"

> *"Windows should always be open allowing real air in the building."*

In addition to providing individualized comfort, adaptive opportunities support low energy consumption goals. While such devices may improve comfort, ideally they are also energy efficient (which could include operable windows and low-energy desk fans, but conventional personal heaters are often very energy-intensive). Multiple building operators noted that adaptive opportunities help maintain comfort in shoulder seasons without having to heat and cool with the radiant system in the same day, which wastes energy and may not lead to comfort due to the slow response time. Air movement devices, such as fans, can reduce energy consumption by comfortably allowing higher cooling air temperature setpoints.

Although adaptive opportunities can be a helpful part of the overall comfort strategy, some occupants may view these devices as mitigation for an inadequate heating or cooling system rather than as an amenity:

> *"Most staff have a heater and/or fan at their workstation to mitigate uncomfortable temperatures."*

> *"Sometimes it feels too warm in my workspace and I have to turn on a personal fan to feel comfortable."*

Even with the most successful centralized heating and cooling systems, there are inter-personal difference in people's comfort preferences, and even the same person might want different conditions throughout the day. As such, the role of these devices should be clearly communicated as a positive personal accessory, not just a way to remediate a failed system.

User-controlled air movement

An advantage of radiant systems is that, because they do not rely on air for heating and cooling, mechanically-supplied air movement is generally low and there is little risk for unwanted air movement (sometimes referred to as draft):

> "*I love that our heating/cooling system is radiant. I love that it's quiet and there isn't air blowing on me*"

However, we know that increased air movement is preferred under neutral to warm temperature sensation (Arens et al. 2009), can create a sense of air freshness (Tian and Love 2008), and can provide comfort with cooling air temperature setpoint several degrees higher than traditional AC (Zhang, Arens, and Zhai 2015). On the other hand, air movement is seen as unwanted when a person already feels cool (Arens et al. 2009; Toftum 2004). As seen in Figure 1, occupants indicated discomfort both from too little and too much air movement. Occupant responses suggest that individual preferences for air movement varies, and that they are dissatisfied when they have little to no control over air movement.

Occupants across seven of the buildings cited discomfort from too little air movement. To introduce air movement, six buildings have operable windows in at least some portions of the building, four buildings use ceiling fans, and several provide or allow desk fans for individual air movement. The buildings or spaces that have the majority of "air movement too low" votes are those without operable windows and in which occupants tend to feel too warm. Strategies such as operable windows and personal fans provide desired air movement for occupants, but comments also suggest that occupants did not consider ceiling or personal fans as part of the primary strategy when responding to this question. This could potentially improve with occupant education and presentation of the HVAC strategy.

> "*Nearly zero air movement without my personal fan.*"
>
> *"It gets a little hot and stuffy in the summer and everyone in an office relies on fans to keep airflow circulating."*

In one particular building, most "air movement too low" votes come from occupants that sit in private offices where a construction error blocked the return path for ventilation. These spaces are prone to overheating and generated comments that there is "no ventilation" or "no air circulation".

Discomfort due to too much air movement is primarily due to non-user-controlled air movement when occupants feel too cool. The majority of responses (88%) for "air movement too high" come from buildings where air movement is not user-controlled: automated windows

(Building 3) and automated ceiling fans that serve approximately 20 occupants per control (Building 6). Similarly, 35% of responses for “drafts from vents” come from Building 4 with automated trickle vents letting in outside air. The automated devices introduce air movement before occupants feel warm enough for it to be comfortable:

> “*The windows often open for airflow or for (what I assume) is anticipated higher temperatures later in the day, often leaving our space too cold*.” (Building 3)
>
> “*Outside air blasting through the trickle vent can be ice cold & create pools of cold air in cubicles close to the windows*.” (Building 4)
>
> *“Overhead fans in the past have gone on way too early and it seems to be too cool.”* (Building 6)

In addition to Building 6, occupants in buildings with ceiling fans felt differently or confused about when or how fans should operate, as was also observed in field studies of ceiling fans in commercial buildings (Present et al. 2019; Lipczynska, Schiavon, and Graham 2018). Ceiling fans are used for multiple reasons, not all of which are for direct occupant cooling. In the four buildings with ceiling fans, the building automation system controls fans usually in groups that affect between four to 20 occupants. It appears that individual air movement preferences are not always satisfied with ceiling fans:

> *“Fans don't come on at the right times to make a difference in the summer, and come on in the winter, when they are not needed?”*

Personal control over air movement is an important factor for acceptability (Toftum 2004). In support of this, ASHRAE 55 does not have an upper limit on air velocity when local air movement is user-controlled, but limits it to 0.8 m/s when it is not user-controlled (e.g., about 2 °C cooling effect). Supporting this, we see that strategies such as desk fans and manually operable windows received positive feedback and can theoretically achieve greater cooling effect by providing air movement that exceeds 0.8 m/s, as specified by ASHRAE Standard 55. However, operable windows in open plan spaces generally affect more than one occupant.

Radiant temperature uniformity and overall temperature predictability

Less than 10% of dissatisfied occupants identified hot or cold walls, windows, or ceilings as the source of discomfort, and only 11% identified floors. Occupants did not specifically reference hot or cold surfaces in their feedback. We observed that the buildings had well insulated envelopes and shading strategies to avoid direct solar heat gains, which is necessary for the radiant systems relatively low heating and cooling capacities. High temperature uniformity within the space could be a result of all surfaces exchanging heat with the controlled active radiant surface with limited surface temperature variations from external walls.

Uniform thermal conditions is a commonly cited reason for thermal comfort in radiant buildings. Building operators also suggested that, from their observations, more uniform temperatures occur in radiant conditioned buildings than in all-air buildings, and several attributed fewer hot or cold spot complaints to this. However, there are different interpretations of what is meant by uniform conditions, including small vertical temperature gradient (Babiak, Olesen, and Petras 2009; Catalina, Virgone, and Kuznik 2009; Li et al. 2015) and uniform spatial distribution of temperature or comfort conditions (i.e., PMV) (Le Dréau and Heiselberg 2014; Catalina, Virgone, and Kuznik 2009; Li et al. 2015). For example, the REHVA guidebook (Babiak, Olesen, and Petras 2009) states, without citation to a study, that, "one of the main features of radiant floor heating is the uniform vertical temperature conditions from floor to ceiling." However, few studies have extensively explored uniformity, and in fact, research suggests that humans may actually prefer and benefit from variable conditions (Kellert, Heerwagen, and Mador 2011; Miura and Ikaga 2016)

Without temperature measurements, we cannot report whether spatial, vertical, or temporal uniform conditions existed in the eight buildings. When there was occupant feedback about temperature, it was almost always in reference to uncomfortable temperatures; occupants in open-plan offices typically referenced the space (or building) being too warm or too cool everywhere rather than in their particular workstation, but they rarely implied that spatial differences in temperature led to discomfort. Those without temperature complaints of too warm or too cool did not provide feedback, so we cannot confirm whether uniformity does or does not influence thermal comfort. It does appear, however, that predictability of conditions, including throughout a space, throughout a day, or from day-to-day, improves comfort.

> *"The temperature is always fantastic, never too hot or too cold, there are no spots in the building where the temperatures vary significantly."*
>
> *"There seems to be no consistency as to when this [being too cool] happens as it feels as if the temperature can change at any time of day and any time of year."*

No single optimum radiant design or control strategy for occupant comfort

Research around design and operation of radiant systems, especially thermally massive systems, has mostly focused on energy consumption while also maintaining appropriate indoor temperatures as assessed through physical measurements or simulation. Through our review, we did not identify any single optimal radiant design or control strategy to maximize occupant comfort. Given the complexity of buildings, perhaps this was not surprising. Each of the buildings had slightly different radiant system designs and controls, combined with a large number of differences in overall building design and features. Therefore, we did not have enough samples to properly compare and generalize findings for the control strategies and radiant features. From the eight buildings, there does not appear to be a relationship between temperature satisfaction and the following design features:

- Primary radiant surface (ceiling, floor, or both);

- Whether the radiant loop control is for variable or constant supply temperature and variable or constant flow;
- System operation outside of occupied hours (e.g., 24/7, 24/7 with setbacks, or turns on before occupancy), which may influence temperatures at the beginning of the day;
- The temperature setpoint strategy (e.g., controlled to zone air temperature, controlled to slab temperature, controlled to supply or return water temperature)

Miscellaneous sources of (dis)comfort and outliers:

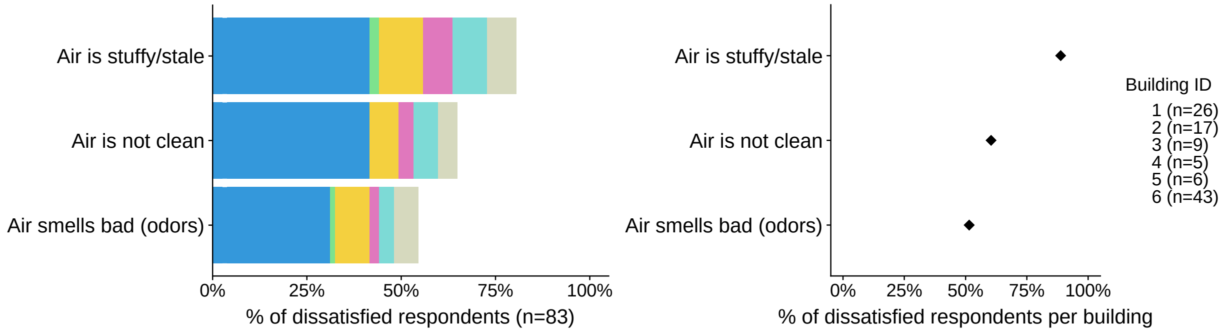
There are sources of comfort/discomfort that were unique to one or two buildings, but could be relevant for other buildings outside this dataset. These include:

- Humidity levels (too high or too low) were not identified as a problem in any of the buildings. Only one building was in a climate that experiences high relative humidity during cooling months (summer wet bulb temperature around 23 °C).
- Supplementary air-cooling systems in at least two buildings appear to be a cause of comfort complaints, including over-cooling in warm weather.
- The building with the most votes for “my area is colder than others” has this problem year-round and is in a warm-humid climate. The building has a supplemental air system for latent loads and when sensible loads exceed the radiant capacity. The air temperature setpoint is 23 °C in cooling, which is the lowest of the dataset. Although not conclusive, the supplemental cooling system and low setpoint could be contributing factors to overcooling in the summer.
- Zones that serve both open and private office spaces could pose a potential concern. There appears to be an association between “my area is hotter than others” complaints in private offices, and “my area is cooler than others” in open offices, even after excluding the building where a construction error blocks the ventilation pathway for private offices. It is common for temperature sensors to be located in open offices in this scenario. Without physical measurements in the spaces, we can only speculate that designers should take consideration of this, and that adaptive opportunities, such as PCS or operable windows could maintain individual comfort.
- One building that has relatively high occupant satisfaction had low occupant density relative to other buildings, which could contribute to both temperature satisfaction due to low internal heat gains, as well as with acoustics.

4.4. Perceived Indoor Air Quality

As seen in Table 1, seven of the buildings had satisfaction (i.e., votes of +1 (‘slightly satisfied’) to +3 (‘very satisfied’)) with air quality between 60 and 90% of respondents, and the three best overall performing buildings had over 80% of respondents satisfied. For the building with poor satisfaction, only 46% of respondents were satisfied. Figure 2 shows the survey results for the three provided sources of air quality dissatisfaction; 83 of 568 respondents were dissatisfied with air quality and stuffy/stale air is voted as the top cause across all buildings.

Figure 2. Indoor air quality sources of dissatisfaction



As shown in Table 3, all buildings use DOAS and about half use overhead mixing diffusers and half use low-level ventilation (e.g., underfloor or displacement ventilation); one building uses trickle vents at window height and had 83% of respondents satisfied with air quality. There does not appear to be a relationship between IAQ satisfaction and the type of ventilation distribution; although, we do not have air quality measurements to compare pollutant concentrations, and at least one building with overhead missing diffusers had several comments about poor air quality and dust:

> *"A higher volume of air from the HVAC might possibly improve air quality in the area."*
>
> *"We just need better air ventilation circulation and someone to clean all the dust.*

This could be caused by lower levels of supply air (not just fresh air) than occupants are used to from all-air systems. This building also had complaints for too low of air movement and too warm of temperatures which could be the primary causes of IAQ dissatisfaction.

This trend appears across the dataset; buildings with lower IAQ satisfaction also tended to have lower temperature satisfaction (and often felt too warm) and more instances of discomfort from too low of air movement relative to the rest of the dataset. This supports previous research that perception of IAQ is tied to thermal comfort, including temperature and air movement, more so than pollutant concentrations at typical exposure levels (Zhang, Arens, and Pasut 2011; Humphreys, Nicol, and McCartney 2002; Fang et al. 2004; Melikov and Kaczmarczyk 2012). Dissatisfied occupants often described the indoor conditions as "stale", "muggy", had "no ventilation", or had "no air circulation", all of which can be associated with temperature and air movement. As further evidence of the relationship between thermal comfort and perceived IAQ, respondents often provided feedback of air being "stale" and "muggy" for both temperature and IAQ categories.

4.5. Acoustics

Acoustics (including noise and sound privacy) has low satisfaction, with the percent satisfied (i.e., votes falling between ‘+1’ (‘slightly satisfied’) and ‘+3’ (‘very satisfied’)) ranging from 24% to 57% per building, as seen in **Error! Reference source not found.**.

Table 5: Acoustical satisfaction by building

Bldg. ID	# of occupant responses (response rate)	Percentage reported for acoustical satisfaction considering votes from (+1) to (+3)		
		% satisfied with noise	% satisfied with sound privacy	% satisfied with acoustics(a)
B1	78 (62%)	35%	14%	25%
B2	28 (37%)	39%	32%	40%
B3(b)	*17 (20%)*	*58%*	*43%*	*57%*
B4(b)	*23 (27%)*	*68%*	*45%*	*51%*
B5(b)	*47 (4%)*	*51%*	*15%*	*26%*
B6	91 (48%)	41%	11%	24%
B7	36 (53%)	36%	14%	25%
B8(b)	*207 (28%)*	*46%*	*25%*	*37%*

(a) Acoustic satisfaction score is calculated as the average satisfaction score of noise and sound privacy per respondent

(b) The buildings indicated in italic had a response rate lower than 35%

There is lower satisfaction with sound privacy than noise, and the primary causes of acoustical dissatisfaction, as seen in Figure 3, are more closely aligned with sound privacy, as are the majority of open-ended responses. The primary space type in these buildings is open plan office, which is detrimental to sound privacy. In current design practice, radiant systems push designs towards more open plan space. However, there are other stronger factors driving designs towards open plans (such as higher occupant densities, affordability, flexibility of the space) and therefore, we cannot attribute the cause entirely to radiant systems alone.

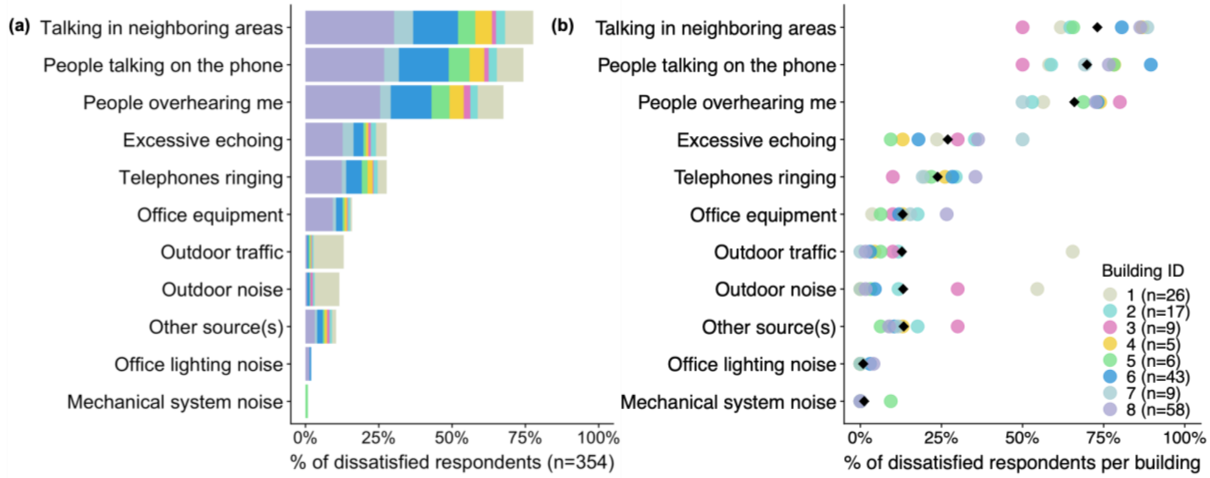


Figure 3. Percentage of dissatisfied occupants across all eight buildings (n=354) and (B) Percentage of per building for each of the potential sources of acoustical discomfort (n by building). The black diamond represents the average percent dissatisfied across each of the individual buildings.

Excessive echoing and telephones ringing, which are less frequently selected, could also be indirectly associated with the highly reflective surfaces like the following comments exemplify:

> *"Lack of ceiling tile creates an echo chamber."*
>
> *"The building tends to echo quite a bit, I can hear people on first level all the way to the third level."*

As speculated by the design community, very few respondents identified mechanical equipment as an issue, which supports statements that radiant systems are quiet, but 16% selected office equipment as a problem. In the building where this was primarily a problem, the issue appears to be two-fold: improperly sized ventilation diffusers that create a whistling noise and noisy ceiling fans, neither of which are directly related to the radiant system.

> *"The mechanical heating and cooling system is very quiet."*

Strategies in place to reduce noise issues in the studied buildings include white noise generators (in one building) and vertically hung acoustic panels (in one building), and carpeted floors (in one building). No building involved horizontally hung acoustic clouds. The building with carpet on portions of the radiant floor has 51% of the occupants satisfied with acoustics (the second highest of all buildings). The building also has low occupant density, which could contribute to lower sound pressure levels in the space. The other two solutions do not appear to be highly affective based on comments and satisfaction scores. Outdoor noises are primarily a problem in Building 3 with automated windows and occupants' comments confirm that is an issue. There also happened to be nearby construction at the time of the survey that could have influenced responses.

Acoustics continue to be a main area of design concern in buildings, much of it having to do with open plan office and sound privacy. This confirms the results from the quantitative survey study on 60 buildings.

4.6. Operation and maintenance

A benefit of radiant systems that has not been widely highlighted amongst the design community is improvements to building operation work load. Each of the six building operators had previous experience in traditional all-air buildings and all had a positive feedback about how radiant systems impact their work. Their reasons include that the system is generally hands free, reduces the physical area of work to mostly the manifold and out of occupant areas, and has fewer mechanical parts for maintenance and repair.

When asked about thermal comfort in the buildings, operators suggested that comfort complaints may be rarer in radiant buildings for social reasons. They explained that because zones are usually serving a large area with many occupants, occupants refrain from making temperature requests because it will impact others. However, this is speculative, and we did not see evidence of this in the occupant survey responses.

Overall, the operators were generally pleased with the system's ability to provide energy efficient comfort. All operators felt that radiant systems are more energy efficient compared to their experience with all-air systems, but some felt that they did not achieve as good of thermal comfort. The operators of two buildings acknowledged that they struggle with having less granular control and ability to individually address comfort compared to all-air systems, particularly in large open office area. The operators in one of these buildings implied that they make ad hoc changes to setpoints to try to improve comfort. However, this building had generally low temperature satisfaction and complaints about daily changing temperatures, so their efforts to control the system more akin to an all-air system is likely working against them. On the other hand, the operator in a building with relatively small radiant zones (many less than 50 m^2) felt the radiant was able to achieve acceptable thermal comfort, if not better than an all-air system.

5. Conclusions

We conducted a post-occupancy assessment in eight buildings using radiant heating and cooling systems. This study follows-up on a quantitative assessment of 60 office buildings that found that radiant and all-air spaces have equal indoor environmental quality, including acoustic satisfaction, with a tendency towards improved temperature satisfaction in radiant buildings. We investigated occupant survey responses in all eight buildings and interviewed building operators in six buildings. None of the building achieve an 80% thermal satisfaction rate (defined as people expressing satisfaction (from +1 to +3) with the temperature). The primary factors leading to temperature discomfort in these buildings is lack of control over the thermal environment, both for temperature and air movement, and slow system response due to the high thermal mass. Features that appear to resolve the comfort issues are fast-response adaptive opportunities, such as operable windows that allow for group control, and/or personal fan that allow for individual control of environmental conditions. Other factors contributing to temperature satisfaction are low risk for unwanted air movement in heating; predictable temperatures; and low risk of discomfort from hot or cold surfaces. We did not find a radiant system design or control scheme that maximize thermal comfort.

IAQ satisfaction tended to align more with temperature satisfaction than ventilation distribution type. Acoustics had low satisfaction across all eight buildings, and most issues stem from sound privacy in open plan offices. Future studies should focus on strategies to improve acoustical satisfaction in radiant buildings with highly reflective surfaces, such as use of carpets and acoustical panels, as well as open plan settings in general.

The four lowest energy consuming buildings take advantage of passive cooling and natural ventilation, and one building relies entirely on natural ventilation. Three buildings also avoid heating and cooling in the same day which is ineffective and energy intensive for high thermal mass systems. Many buildings have high performance envelopes and sun shading strategies.

High thermal mass radiant buildings could provide flexibility and opportunity for resiliency, and more can be uncovered with their increasing popularity in building designs.

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